

ASRDI OXYGEN TECHNOLOGY SURVEY

Volume VIII:

Pressure Measurement

ARVIDSON and BRENNAN

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ASRDI OXYGEN TECHNOLOGY SURVEY

Volume VIII:

Pressure Measurement

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Prepared for the
Aerospace Safety Research and Data Institute
NASA Lewis Research Center



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PREFACE

This publication is part of an oxygen safety review in progress by the NASA Aerospace Safety Research and Data Institute (ASRDI). The objectives of the review include:

1. Recommendations to improve NASA oxygen handling practices by comparing NASA and contractor oxygen systems including the design, inspection, operation, maintenance, and emergency procedures.
2. Assessment of the vulnerability to failure of oxygen equipment from a variety of sources so that hazards may be defined and remedial measures formulated.
3. Contributions to safe oxygen handling techniques through research.
4. Formulation of criteria and standards on all aspects of oxygen handling, storage, and disposal.

The special publication summarizes the current state-of-the-art in pressure measurement in the region of 50 to 150 K (the liquid state of oxygen). The report is not limited to oxygen-proved systems alone as this would have severely limited the report. The published literature available in the cryogenic region generally is quite restricted. The survey includes information on cleaning and materials compatibility, calibration methods and descriptions of representative transducers. A summary of recommendations is presented as well as an extensive bibliography arranged by transducer type.

This work was initiated by Frank E. Belles, former Director of ASRDI.

Soloman Weiss, Acting Director
Aerospace Safety Research and
Data Institute
National Aeronautics and
Space Administration

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FOREWORD

It is hoped that this report will provide an up-to-date viewpoint of pressure transducers and their current uses with gaseous or liquid oxygen. Very little data are available in the literature on pressure transducers with respect to gaseous and liquid oxygen. Therefore, all transducer types such as strain gage, capacitance, potentiometric, piezoelectric, etc., are included in this survey.

Some of the topics covered include cryogenic pressure measurement, material compatibility with gaseous and liquid oxygen, cleaning procedures, pressure tap connections, transducer types and description, and calibration techniques.

Since much is known about a relatively few pressure transducer types (relating to gaseous and liquid oxygen service), recommendations by the authors were made when other information was unavailable. Where possible, range, performance, and endurance comparisons have been made between transducer types.

We wish to thank Michael C. Jones of the NBS Cryogenics Division and ASRDI Project Manager Paul Ordin of the NASA-Lewis Research Center for their review and constructive comments during the course of this project. Harlan S. Harman, Chief of the Pressure and Thrust Section at George C. Marshall Space Flight Center, also provided several unpublished NASA reports on pressure transducer performance and for these we wish to thank him. Finally, we are indebted to Shirley A. Alldredge and staff of the NBS Boulder Library for their help in acquiring the numerous references, without which this report could not have been written.

John M. Arvidson

James A. Brennan

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CONTENTS

1.	INTRODUCTION	1
2.	CRYOGENIC PRESSURE MEASUREMENT	12
3.	MATERIAL COMPATIBILITY WITH GASEOUS AND LIQUID OXYGEN	22
4.	TRANSDUCER CLEANING PROCEDURES	24
5.	PRESSURE TAP CONNECTIONS	27
6.	TRANSDUCER TYPES AND DESCRIPTION	33
	Force-summing elements	
6.1	Manometer	33
6.2	Bourdon Tube	41
6.3	Diaphragm	51
6.4	Bellows	57
	Pressure transducers with force-summing element	
6.5	Strain	65
6.6	Capacitance	74
6.7	Piezoelectric	81
6.8	Potentiometric	88
6.9	Inductance	95
6.10	Reluctance	99
6.11	Micromanometers	105
6.12	Vibrating Wire	107
6.13	Optical	111
6.14	Diode	115
6.15	Electrokinetic	119
6.16	Magnetostrictive	122
6.17	Ohmstrictive	124
6.18	Force Balance	126
6.19	Oscillating	128
6.20	Photoelectric	130
7.	LOW-TEMPERATURE CALIBRATION METHODS	132

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LIST OF FIGURES

		Page
Figure 1.1	Ranges of some commercially available gages	5
Figure 1.2	The comparison of some force-summing elements and vacuum pressure transducers	7
Figure 2.1	Effect of thermal cycling on bonded strain gage pressure transducers	14
Figure 2.2	Temperature compensation and the effect on pressure transducer sensitivity	16
Figure 2.3	The effect of temperature on pressure transducer performance for two similar transducers (same type, mfg., etc.) Transducer type: strain gage	18
Figure 2.4	The effect of temperature on pressure transducer performance for two similar transducers (same type, mfg., etc.) Transducer type: linear variable differential transformer.	19
Figure 2.5	The effect of temperature on pressure transducer performance for two similar transducers (same type, mfg., etc.) Transducer type: variable reluctance.	20
Figure 5.1	Transducer locations	27
Figure 5.2	Pressure taps and the effect of hole size	32
Figure 5.3	Pressure taps and the effect of hole geometry	32
Figure 6.11	U-tube	34
Figure 6.12	Differential	35
Figure 6.13	Cistern	36
Figure 6.14	Inclined	36
Figure 6.21	Bourdon tube configurations	41
Figure 6.22	C-type bourdon tube geometry	42
Figure 6.23	Optical pressure transducer utilizing a helical bourdon tube	47
Figure 6.31	Basic diaphragm types	51
Figure 6.32	Slack diaphragm pressure gage	52
Figure 6.41	Common types of bellows and fitting attachment methods	57
Figure 6.42	Bellows gage for measuring differential pressure	58
Figure 6.43	Temperature compensated differential pressure bellows gage	59
Figure 6.44	Cyclic life of bellows	63

LIST OF FIGURES (continued)

		Page
Figure 6.51	Bonded and unbonded strain gages and associated circuitry	66
Figure 6.52	Typical unbonded strain gage installation	68
Figure 6.53	Electrical circuitry necessary for bonded or unbonded strain gage pressure transducer	69
Figure 6.61	Parallel-plate capacitive pressure transducer	74
Figure 6.62	Concentric overlapping cylinder capacitive pressure transducer	75
Figure 6.63	Transducer output vs displacement for dielectrics of various thickness	75
Figure 6.64	Electrical circuitry for capacitance pressure transducers	78
Figure 6.71	Schematic of piezoelectric pressure transducer and related circuitry	80
Figure 6.72	The response characteristics of a piezoelectric pressure transducer	82
Figure 6.73	Piezoelectric crystal sensitivity	83
Figure 6.74	Piezoelectric crystals stacked in parallel	84
Figure 6.75	Block diagram for piezoelectric pressure transducers	85
Figure 6.81	Potentiometric pressure transducer using a capsule element	89
Figure 6.82	Circuitry for potentiometric devices	89
Figure 6.83	Potentiometric pressure transducer using a bourdon tube element	89
Figure 6.84	Error contribution in a pressure transducer	90
Figure 6.85	Pressure transducer component isolation for use with reactive liquids or gases	91
Figure 6.91	Inductance technique commonly used in pressure transducers	95
Figure 6.92	Inductance-ratio circuitry	96
Figure 6.93	Output vs armature displacement for LVDT pressure transducers	97
Figure 6.94	Inductance pressure transducer circuitry	97
Figure 6.101	Basic principle of reluctance technique	100
Figure 6.102	Circuitry for reluctance pressure transducers	101
Figure 6.103	Block diagram of reluctance pressure transducer circuit	102

LIST OF FIGURES (continued)

	Page
Figure 6.121 Vibrating wire pressure transducer	107
Figure 6.122 Sensitivity dependence on the thermal history of the vibrating wire element	108
Figure 6.131 Schematic of a basic optical pressure sensing device	112
Figure 6.141 Tunnel diode oscillator	116
Figure 6.142 Diode output (mV) vs pressure (psi) at various temperatures	117
Figure 6.143 Diode frequency vs pressure	117
Figure 6.151 Electrokinetic pressure transducer	119
Figure 6.161 Magnetostrictive pressure transducer	123
Figure 6.171 Ohmstrictive pressure transducer	124
Figure 6.181 Force-balance pressure transducer	126
Figure 6.191 Oscillating pressure transducer	128
Figure 6.201 Photoelectric pressure transducer	130
Figure 7.1 Cryogenic pressure transducer calibration system	133
Figure 8.11 Low-pressure deadweight tester	134
Figure 8.12 High-pressure deadweight tester	135
Figure 8.13 Typical deadweight tester system	144
Figure 8.21 Shock tube calibration system	147
Figure 8.31 Siren-tuned-cavity generator	149
Figure 8.41 Rotating-valve pulse-function generator	151
Figure 8.42 Rotating-valve step-function wave form	152
Figure 8.51 Low-frequency pneumatic sinusoid generator (piston-in-cylinder model)	153
Figure 8.61 Arrangement for calibration using the electromagnetic technique	154
Figure 9.1 Static and dynamic cryogenic pressure sensor test facility	158
Figure 9.2 Static and dynamic pressure cell assembly	159

LIST OF TABLES

		Page
Table 1.1	Specifications of some commercially available pressure gages	3
Table 1.2	Pressure transducers	4
Table 4.1	Cleaning and inspection procedures for ballistic missile systems	24
Table 4.2	Cleaning of oxygen pressure gage components, naval boiler, and turbine laboratory	25
Table 4.3	Cleaning and testing of oxygen and nitrogen gas piping systems	25
Table 4.4	Cleaning methods and processes	26
Table 5.1	Summary of formulas	29
Table 6.11	Manometer fluid densities	33
Table 6.12	Boiling point and vapor pressure of some manometer fluids	38
Table 6.31	E and K values for commonly used materials	56
Table 6.41	Characteristics of single-ply brass bellows	61
Table 6.51	Gage factor and temperature coefficient for some strain gage materials	66
Table 6.52	Characteristics of pressure transducers using strain gages	72
Table 8.11	Gravity vs latitude	142
Table 8.12	Effective diameter	143
Table 8.13	Weight tolerance	143

CONVERSION FACTORS

There are a multiplicity of terms used in pressure measurement. The International System of Units (SI) recognizes the Pascal (Pa) (Newtons/metre²) as the accepted unit of pressure or stress. Accordingly, the following conversion factors are given to convert other commonly used terms to Pascal^[G56]. Also, additional conversion factors are provided since no attempt was made to convert the units found in the literature to SI.

To convert from	To	Multiply By
<u>Density</u>		
gram/centimeter ³	kilogram/meter ³	1.00×10^3
lbm/inch ³	kilogram/meter ³	2.7679905×10^4
lbm/foot ³	kilogram/meter ³	1.6018463×10^1
slug/foot ³	kilogram/meter ³	5.15379×10^2
<u>Length</u>		
angstrom	meter	1.00×10^{-10}
foot	meter	3.048×10^{-1}
inch	meter	2.54×10^{-2}
meter	wavelengths Kr 86	1.65076373×10^6
micron	meter	1.00×10^{-6}
mil	meter	2.54×10^{-5}
yard	meter	9.144×10^{-1}
<u>Mass</u>		
carat (metric)	kilogram	2.00×10^{-4}
gram	kilogram	1.00×10^{-3}
kilogram mass	kilogram	1.00×10^0
lbm (pound mass, avoirdupois)	kilogram	4.5359237×10^{-1}
ounce mass (avoirdupois)	kilogram	$2.8349523125 \times 10^{-2}$
pound mass, lbm (avoirdupois)	kilogram	4.5359237×10^{-1}
slug	kilogram	1.45939029×10^1
<u>Pressure or Stress (Force/Area)</u>		
atmosphere (technical = 1 kgf/cm ²)	pascal (Pa)	9.806650×10^4
bar	pascal (Pa)	1.00×10^5
centimetre of mercury (0°C)	pascal (Pa)	1.33322×10^3
centimetre of water (4°C)	pascal (Pa)	9.80638×10^1
decibar	pascal (Pa)	1.00×10^4
dyne/centimetre ²	pascal (Pa)	1.00×10^{-1}

* Exact.

To convert from	To	Multiply By
<u>Pressure or Stress (Force/Area) (continued)</u>		
foot of water (39.2°F)	pascal (Pa)	2.98898 x 10 ³
gram-force/centimetre ²	pascal (Pa)	9.806650* x 10 ¹
inch of mercury (32°F)	pascal (Pa)	3.386389 x 10 ³
inch of mercury (60°F)	pascal (Pa)	3.37685 x 10 ³
inch of water (39.2°F)	pascal (Pa)	2.49082 x 10 ²
inch of water (60°F)	pascal (Pa)	2.4884 x 10 ²
kilogram-force/centimetre ²	pascal (Pa)	9.806650* x 10 ⁴
kilogram-force/metre ²	pascal (Pa)	9.806650* x 10 ⁰
kilogram-force/millimetre ²	pascal (Pa)	9.806650* x 10 ⁶
kip/inch ² (ksi)	pascal (Pa)	6.894757 x 10 ⁶
millibar	pascal (Pa)	1.00* x 10 ²
millimetre of mercury (0°C)	pascal (Pa)	1.333224 x 10 ²
poundal/foot ²	pascal (Pa)	1.488164 x 10 ⁰
pound-force/foot ²	pascal (Pa)	4.788026 x 10 ¹
pound-force/inch ² (psi)	pascal (Pa)	6.894757 x 10 ³
psi	pascal (Pa)	6.894757 x 10 ³
torr (mm Hg, 0°C)	pascal (Pa)	1.33322 x 10 ²
Newton/metre ²	pascal (Pa)	1.00*
<u>Temperature</u>		
Celsius (temperature)	Kelvin	K=C+273.15
Fahrenheit (temperature)	Kelvin	K=(5/9) (F+459.67)
Rankine (temperature)	Kelvin	K=(5/9) R
Fahrenheit (temperature)	Celsius	C=(5/9) (F-32)
Kelvin (temperature)	Celsius	C=K-273.15
<u>Viscosity</u>		
lbm/foot second	newton second/meter ²	1.4881639 x 10 ⁰
lbf second/foot ²	newton second/meter ²	4.7880258 x 10 ¹

Multiplication Factors

1 000 000 000 = 10 ⁹
1 000 000 = 10 ⁶
1 000 = 10 ³
0.001 = 10 ⁻³
0.000 001 = 10 ⁻⁶
0.000 000 001 = 10 ⁻⁹

Prefix

giga
mega
kilo
milli
micro
nano

SI Symbol

G
M
k
m
μ
n

* Exact.

1. INTRODUCTION.

Of all the measurements made on systems, one of the most common must surely be that of pressure measurement. Pressure measurements are made not only to determine the force per unit area in a system, but also to determine flow rate (head type meters), quantity (differential pressure liquid level gages), and temperature (vapor pressure or gas thermometers). There are, understandably, a wide variety of pressure measuring devices in existence. The devices and methods described in this report were selected after an extensive review of the available literature. A comprehensive reference and bibliography list is provided at the end of this publication which was compiled from several sources including a search of the NBS Cryogenic Data Center and the NASA Scientific and Technical Information Facility. Very few references in the literature deal with the problem of pressure transducers and their performance in cryogenic environments, and in particular, when used with liquid oxygen (LOX). Therefore, an accurate evaluation is not available. This report, however, is not limited to those references which were only concerned with oxygen (gaseous and liquid). Where the information was not available, a quantitative discussion was made.

As many considerations as possible (i.e., calibration, error, oscillations, hysteresis, etc.) for pressure transducers at cryogenic temperatures will be covered in this report and wherever possible the discussion will be quantitative. Problem areas connected with a particular pressure transducer and the considerations mentioned will be discussed in the appropriate section (i.e., diaphragm, bellows, etc.) followed by descriptions, performance (mostly at ambient conditions), and other pertinent data. The above approach is felt to be the most practical since very few data are available in the literature on pressure transducers with respect to gaseous and liquid oxygen. Recommendations by the authors will be made when other information is unavailable.

Instruments for making both static and dynamic pressure measurements are described. Even in nominally static pressure systems dynamic pressure fluctuations may be present, as in a flowing stream or a differential liquid level gage. Thermal oscillations in lines containing cryogenic fluids present special problems which can be quite detrimental in obtaining a "true" pressure reading (see "Cryogenic Pressure Measurement"). Therefore, it is very important that the system characteristics be properly considered when choosing pressure measuring instrumentation. General information on elastic gages and manometers commonly used in pressure measurement are shown in table 1.1^[G1]*. Also, information on electrical transducers (quite often used in conjunction with a diaphragm, Bourdon tube, or bellows) used to measure pressure is shown in table 1.2^[G11].

Some of the more commonly found pressure measuring devices used for measuring vacuum or low pressures are listed in Figure 1.1. The approximate pressure range, for a particular gage, is also indicated in the figure. Through common usage the term vacuum refers to any pressure below atmospheric. This pressure region has been divided into five generally accepted degrees^[G28]:

Low vacuum	760 torr to 25 torr (101.3 kPa to 3.33 kPa)
Medium vacuum	25 torr to 10^{03} torr (3.33 kPa to 0.13 Pa)
High vacuum	10^{-3} torr to 10^{-6} torr (0.13 Pa to 0.13 mPa)
Very high vacuum	10^{-6} torr to 10^{-9} torr (0.13 mPa to 0.13 μ Pa)
Ultrahigh vacuum	10^{-9} torr and beyond (0.13 μ Pa and beyond)

Under normal conditions vacuum measuring devices are not actually exposed to oxygen (gas or liquid), therefore, they are not covered in this report. For additional information on vacuum measurement the reader is referred to a review paper by Santeler, et. al.^[G29].

* References throughout the text are prefixed by a symbol (e.g., G,C,B, etc.) to denote the category in which they are listed (see list of designations under "References and Bibliography"). An "Author-Designation Cross Reference Index" is also included with authors listed alphabetically.

Table 1.1 Specifications of some commercially available pressure gages.

Type of instrument	Basic element used	Room temperature commercial accuracy at calibration, per cent of span	Maximum uncompensated ambient temperature errors for $\pm 25^{\circ}\text{F}$ change, per cent of span	Maximum static pressure, $^{\circ}\text{F}$ psi	Pressure ranges— minimum and maximum spans (pressure, vacuum, or compound)	Compound ranges available	Vacuum ranges available
Pressure gage	C bourdon	$\pm 1/2$ to ± 1	$\pm 1/4$	200		12 to 100,000 psi	X
Pressure gage	Helical bourdon	$\pm 1/2$ to ± 1	$\pm 1/4$	200		12 to 80,000 psi	X
Pressure gage	Spiral bourdon	$\pm 1/2$ to ± 1	$\pm 1/4$	200		12 to 40,000 psi	X
Pressure gage	Diaphragm (metallic)	$\pm 1/2$ to ± 1	$\pm 1/4$	200	2 in. H_2O to 30 psi	Some to 400 psi	X
Pressure gage	Bel lows (spring-loaded)	$\pm 1/2$ to ± 1	$\pm 1/4$	200	5 in. H_2O to 30 psi	Some to 800 psi	X
Pressure, draft, or differential gage	Diaphragm or differential (spring-loaded)	$\pm 1/2$ to ± 1	15		0.2 to 120 in. H_2O		X
Differential gage	Bel lows (spring-loaded)	$\pm 1/2$ to ± 1	$\pm 1/4$	500	20 to 400 in. H_2O		X
Differential gage	Double bellows	$\pm 1/2$ to ± 1	$\pm 1/4$ or less	3,000	20 to 400 in. H_2O		X
Liquid-level gage (air seal)	Bourdon, metallic diaphragm, bellows	$\pm 1/2$ to ± 1	Negligible for air-seal capacity	150	20 in. to 100 ft. H_2O		-
Volumetric-seal gage	Bourdon	$\pm 1/2$ to ± 1	Depends on range and capillary length	600 (seal)		50 to 10,000 psi	X
Force-balance seal gage	Bourdon, metallic diaphragm, bellows	Not to be used below 2 in. H_2O above, $\pm 1/2$ in. H_2O	Negligible	200-800 (seal design)	12 in. H_2O to 100 psi		-
Differential liquid manometer	Liquid column	$\pm 1/2$ to ± 1	$\pm 1/4$	2,500	10 to 500 in. H_2O		X
Ring-balance manometer	Force on ring	$\pm 1/2$ to ± 1		1,500 to 10,000	20 to 420 in. H_2O		-
Bell-type gage	Force on bell	$\pm 1/2$ to ± 1			0.2 to 40 in. H_2O		X
Bell-type differential gage	Force on bell	$\pm 1/2$ to ± 1			0.2 to 40 in. H_2O		X
Absolute-pressure gage	Diaphragm	± 1	$\pm 1/4$	200	6 to 760 mm Hg abs 3.2 to 405.6 in. H_2O		-
Absolute-pressure gage	Bel lows	± 1				200 mm to 60 in. Hg abs	-
Fixed-clster barometer	Mercury column	Min division 0.1 mm Hg	$< \pm 1/4$ of reading	Ambient	Atmospheric pressure		-
U-type absolute-pressure gage	Liquid column	Min division 0.1 in liquid	$< \pm 1/4$ of reading	Ambient	5 to 50 in. Hg		X
Inclined-tube manometer	Liquid column	Min division 0.01 in liquid	$< \pm 1/4$ of reading	Ambient	0.5 to 50 in. H_2O		X
Manometer well	Liquid column	Min division 0.1 in liquid	$\pm 1/4$ of reading	Ambient	6 to 130 in. liquid		X

Table 1. 2 Pressure Transducers

Characteristic	Strain Gage	Capacitance	Crystal	Reluctance
Frequency response, Hz	to 40 k Hz	to 500 K Hz	0.5 to 1 M Hz	1 K Hz (approx.)
Nominal sensitivity, % full scale	0.5	1.0	0.5	1.0
Thermal stability	Excellent for compensated bridge winding	Approx. temperature drift; 0.025 % per deg F	Good	Approx. 0.02% per deg F
Linearity, %	< 0.1	~ 1.0	0.5	~ 1.0
Response to vibration, noise, acceleration	Negligible for light-diaphragm and fully-rigid types	Low, but noticeable	Can be appreciable; also highly sensitive to electrical "noise"	Low, but noticeable; about 1.0% per 100 G
Drift, %	negligible	1.0 (excluding temperature drift)		2.0
Hysteresis, %	Approx. 0.2	1.0	negligible	0.5
Open-circuit full-scale output	Order of 50 mv	Order of 5 v	Order of 1 mv	Order of 5 v
Overload, %	Generally about 100; to 500 for special types	Order of 100	Satisfactory for elastic limit of crystal; poor for higher loads	Order of 100
Ease of calibration	straightforward	straightforward	No static calibration possible; dynamic calibration tricky	straightforward
Typical pressure sensing device	tube or diaphragm	diaphragm	crystal	diaphragm or twisted torsion tube
Cooling	Some designs air or water cooled (special types have heat-transfer rates to about 7.0 BTU/in ² /s	Some designs air or water cooled (special types have heat-transfer rates to about 7.0 BTU/in ² /s	Generally none possible	Generally none possible
Remarks and limitations	Good all-around. Expensive repair and replacement of parts on high-performance designs	Excellent instrument except for drift. Larger and more complex than strain gage	Unique in ultra-high frequency range. Not useable below about 5 Hz.	Maximum temperature 200 F. Low frequency response

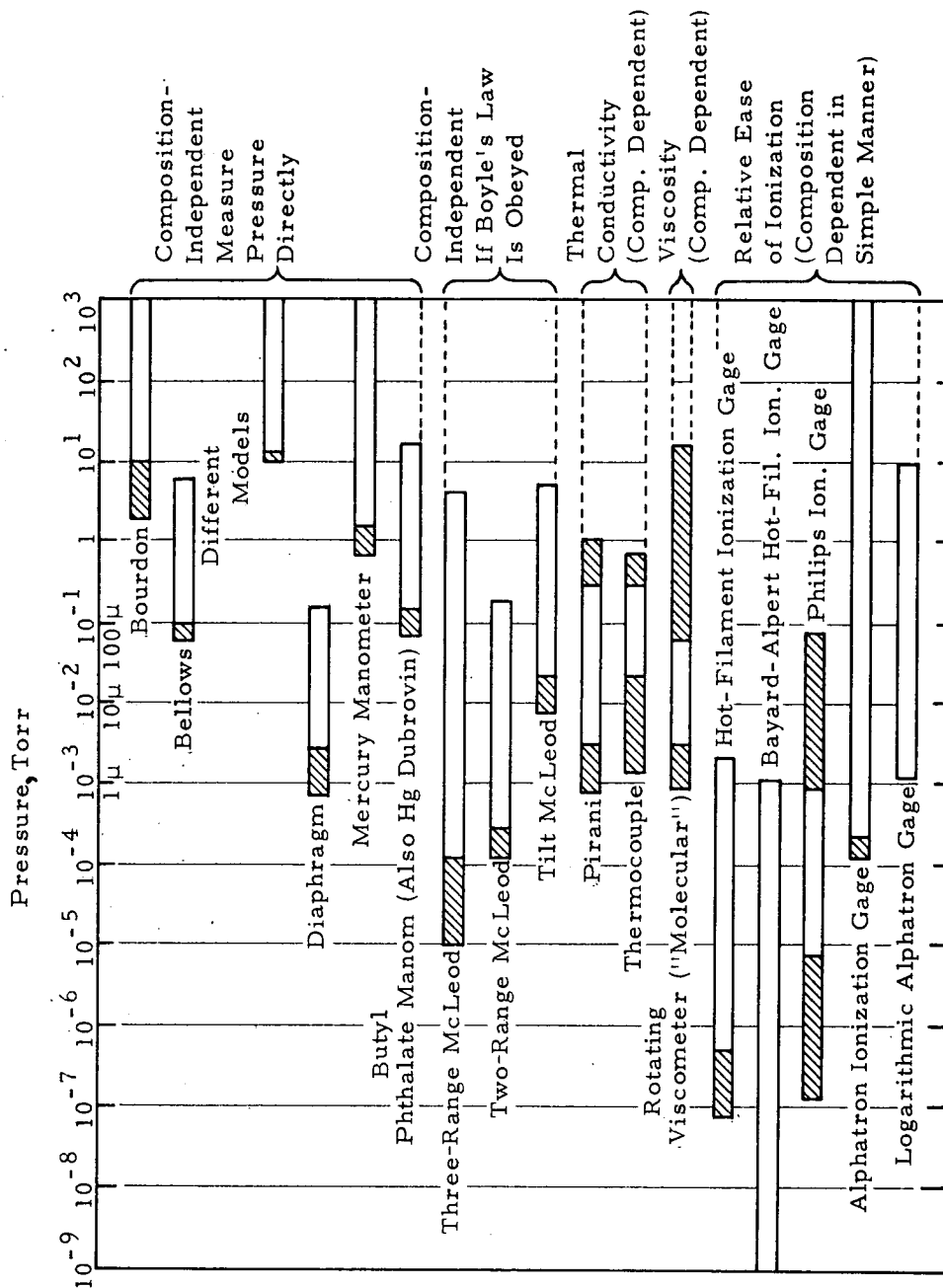


Figure 1.1 Ranges of some commercially available gages [1]

Included in this report are some possible sources for error in making pressure measurements, which would include those at low temperature. Error analysis is only briefly touched upon in this publication since a complete treatment of the subject is beyond the scope of this report. However, the References and Bibliography section lists several good publications dealing with the subject.

Figure 1.2 helps to compare the characteristics of some pressure transducer types^[G1].

Key to Answer Symbols		Bourdon	Bellows	Diaphragm	Manometers	McLeod	Pirani and Thermo- couple	Viscometer "Molecular" Gage	Hot-Filament Ionization	Philips Cold-Cathode Ionization	Seven-Decade Alpha-Source Gage	Logarithmic Alpha-Source Gage
1	Composition Independent?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
2	Leaves Gas Uncontaminated?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3	Uncontaminated by Gas?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
4	Free from Mercury Attack?	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
5	Independent of Gage Temp.?	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
6	Usable at Low Temperature?	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7	Usable at High Temperature?	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8	Continuous Indicating?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9	Remote Indication Easy?	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10	Accuracy 10% or Better?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
11	Wide Range Without Switching?	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
12	Usable in GO_2 ?	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>				
13	Usable in LO_2 ?	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>				
Other Comments		Limited Sensitivity	Limited Sensitivity	Delicate; Vibration & Temperature Sensitive	Mercury Vapor May Amalgamate	Non-Condensable Gases Only	Low-Pressure Calib. Man Drift	Highly Nonlinear Scale	Hot Filament May Injure Gas	Some Gettering by Hi- GH-Voltage Discharge	Radioactive Source	Radioactive Source

Figure 1.2 The comparison of some force-summing elements and vacuum pressure transducers.

Notes for Figure 1.2

1. Composition independent?

"Qualified Yes" for McLeod gage where gas must obey Boyle's law and for Knudsen gage which can be made nearly composition independent, but which is not always so constructed.

"Qualified No" for hot-filament and alpha-source ionization gages.

These gages are composition dependent, but the relative sensitivity to different gases is not a function of pressure and consequently can be expressed simply as a calibration factor or sensitivity ratio.

"Definite No" for Pirani and thermocouple, viscometer molecular gage, Philips cold-cathode ionization gage. The composition dependence here is complex and cannot be expressed by a simple ratio valid for the entire pressure range.

2. Leaves gas uncontaminated?

"Qualified Yes" is assigned to those gages which involve mercury vapor, components heated to incandescence, or high-voltage electrical discharges.

3. Uncontaminated by gas?

"Qualified Yes" is assigned for the following reasons: (1) Mercury manometer and McLeod gage: accuracy of indication will eventually suffer when the mercury and tubing walls become dirty. (2) Hot-filament ionization and Philips cold-cathode ionization gages: appreciable gettering and sorption occur and are troublesome in the lowest part of the pressure range. (3) Alpha-source gages: excessive condensation of moisture or other liquids can affect reading.

"Qualified No" is assigned for the following reason (1) Pirani and thermocouple gages (particularly the latter): low-pressure errors due to change of emissivity.

4. Free from mercury attack?

"Definite Yes" is assigned only to those gages where usual materials and construction are such as to resist attack even by liquid mercury. "Qualified Yes" indicates that gages probably are capable of resisting mercury vapor for extended periods of time, but not necessarily able to withstand action of mercury droplets.

"Qualified No" indicates that precautions are desirable to keep mercury vapor and droplets from gage when operation covers more than a few tens of hours.

5. Independent of gage temperature?

"Definite Yes" signifies that gage indicates pressure rather than molecular density; indication is relatively unaffected by variations in gas temperature or ambient temperature.

"Qualified Yes" is assigned for the following reasons: (1) Knudsen, Pirani, and thermocouple gages operate on the basis of heat transfer through the gas; hence ambient temperature affects indication somewhat. (2) Hot-filament, Philips cold-cathode, and alpha-source gages indicate molecular density rather than pressure.

"Qualified No" signifies: (1) Sensitive diaphragm gages require careful thermostating. (2) Viscometer molecular gage has somewhat severe temperature errors near mid-range.

6. Usable at low temperature?

As rough basis of comparison, "low temperature" here means below the freezing point of water.

"Definite Yes" is assigned only when operating principle is independent of temperature and when generation or conduction of heat is not essential to gage function.

"Qualified Yes" signifies: (1) Mercury manometer and McLeod gage are limited only by low-temperature properties of fluid. (2) Knudsen, Pirani, and thermocouple gages depend on heat conduction--hence must be recalibrated for operating temperature. (3) Viscometer molecular gage has severe temperature dependence at mid-scale. (4) Hot-filament ionization gage contains an intense heat source.

"Qualified No"--Diaphragm gage can be thermostatted to low temperatures, but differential expansion effects are difficult to eliminate from element design.

7. Usable at high temperature?

High temperature here is taken roughly as above the boiling point of water. Essentially the same answers and reasons are assigned as for low-temperature operation.

8. Continuous indicating?

"Definite No"--McLeod, inherently.

9. Remote indication easy?

"Definite Yes" only with a gage whose output is already an electrical signal, including diaphragm, Pirani, thermocouple, and all ionization gages.

"Definite No"--McLeod gage where remote manipulation and reading are relatively impractical. Viscometer molecular gage where indication is by mechanical pointer located inside evacuated enclosure.

10. Accuracy 10 per cent or better?

"Qualified Yes" for fractional accuracy of 10 to 15 per cent.

"Qualified No" for fractional accuracy poorer than 25 per cent at some portion of range.

11. Wide range without switching?

"Definite Yes"--McLeod gage which is available in two-range and three-range models. Viscometer molecular gage uses two different operating principles for two ends of the scale which gives wide operating range. Logarithmic alpha-source gage has logarithmic scale which covers four decades.

"Qualified Yes"--Useful range without switching two to three decades.

"Qualified No"--Useful range without switching less than two complete decades.

12. Useable in gaseous oxygen?

"Qualified Yes"--Can be used if materials selected are compatible with oxygen.

13. Usable in liquid oxygen?

"Qualified Yes"--Through proper design the bellows and diaphragm pressure transducer can be used with liquid oxygen.

2. CRYOGENIC PRESSURE MEASUREMENT

Much is known about the cryogenic performance of a relatively few pressure transducer types; however, the information available is either in the form of manufacturing specifications or unpublished reports. Hayakawa^[G59] made a study of cryogenic pressure measurement technology and concluded that accuracies of 2 per cent full scale were unattainable. The transducer types studied in this report were strain gage (bonded and unbonded), piezoelectric, and potentiometric. Hayakawa states that inquiries "to approximately 50 manufacturers resulted in seven favorable responses from suppliers indicating the availability of transducers operable with cryogenic systems of liquid oxygen or liquid hydrogen". Transducers, at low temperature, usually experience a change in sensitivity, a zero shift, or erratic performance.

For many years pressure measurement in cryogenic systems^[G15,G57,G58,C7] has been made by simply running gage lines from the desired point of measurement to a convenient location at ambient temperature and attaching a suitable pressure-measuring device. In many systems this straightforward method for pressure measurement (excluding vacuum) will work quite well without difficulty; however, there are disadvantages which can create serious problems in a system^[G57]. Three very important items to consider for pressure measurement in a cryogenic medium are: (1) reduced frequency response (if long gage lines are used), (2) pressure oscillations, and (3) heat leak.

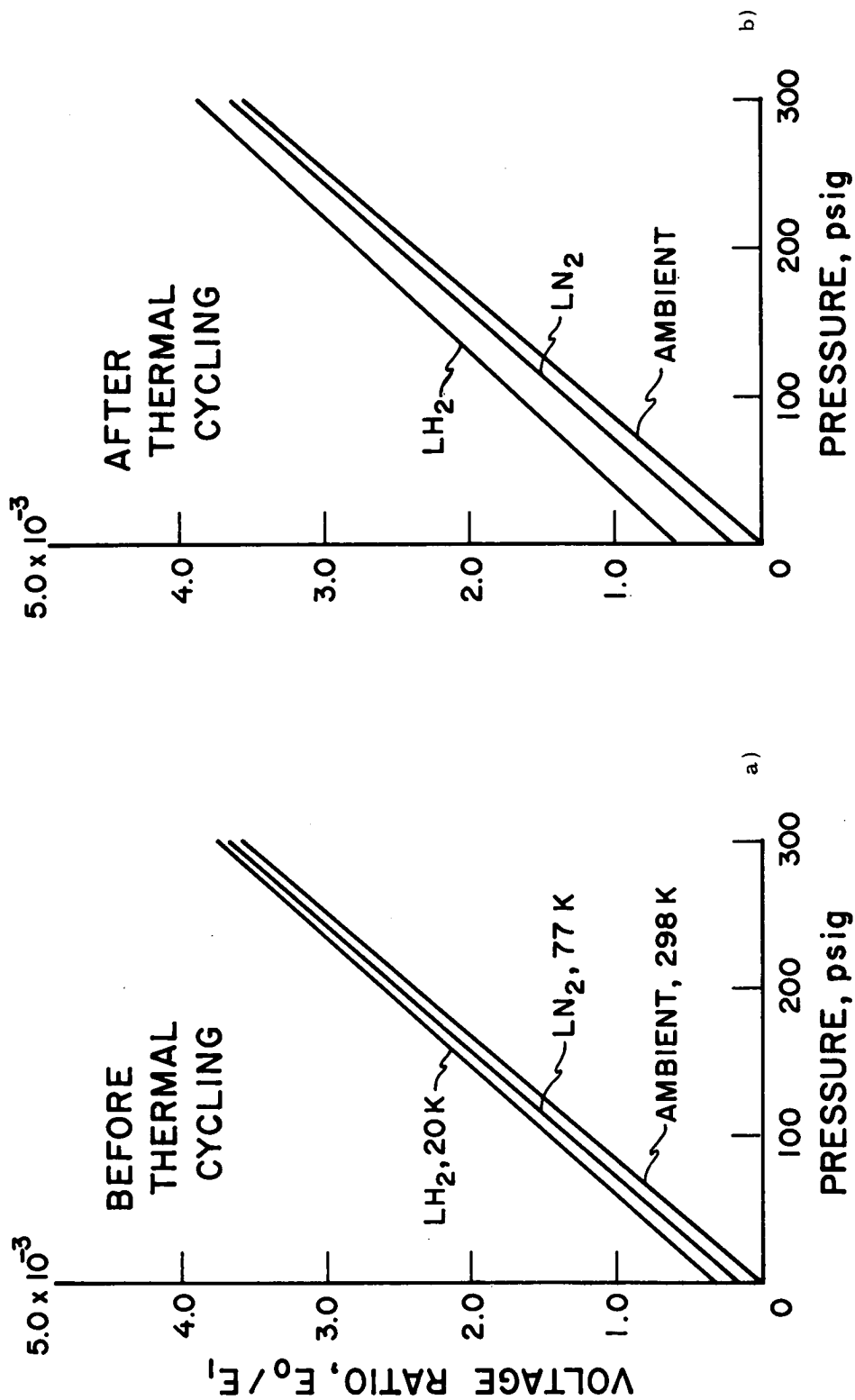
A lengthy run of gage line from cryogenic to ambient environments will, most likely, introduce all three conditions mentioned above. In addition, oscillations in a system can fatigue the piping and result in premature failure. Smelser^[G57] comments about this problem by indicating: "Gauge lines that run from some relatively high-temperature locations into a cryogenic liquid can give rise to pulsations unless care is taken to fix the liquid-vapor interface in the line. This phenomenon is caused when liquid is suddenly forced into a gauge line to a point where the temperature is above the saturation temperature of the liquid. The resultant

pressure rise forces the liquid back in the line, causing a drop in pressure which again allows the liquid to move into the high-temperature region, starting a new cycle". This process can cause oscillations to occur which are quite large and prevent an accurate pressure measurement. "Damping can be introduced in the gauge line, but this, of course, further limits the frequency response of the system. Careful placement of the gauge line (by keeping it horizontal) at the point where it enters the cryogenic fluid can eliminate pulsations under quiescent conditions, but does not necessarily ensure their elimination if pressure surges occur, as might happen during filling or emptying a dewar"[G57].

If a pressure transducer utilizes long runs of small diameter tubing (to minimize heat leak) the limiting factor in frequency response is due to this connecting piping. The solution to the problem is to locate pressure transducers close to the point at which the measurement is desired and, if possible, in direct contact with that source. Some transducers, such as the diodes, may even be installed completely within a vessel or pipe having only the electrical leads exposed to ambient conditions. Some advantages for using this arrangement include greatly increased frequency response, minimal heat leak, elimination of pressure (thermal) oscillations, and possibility for remote monitoring.

Pressure transducers such as those having a diaphragm, bellows, or capsule may be better suited for external applications using the force-summing element (diaphragm, etc.) as the inter-face between the medium being measured and the electronics used in conjunction with that force-summing element. Others, such as the piezoelectric, capacitive, diode, etc., may have the potential (depending on design) to be used better internally. In the "Recommendations" section this subject will be discussed in greater detail with respect to specific transducer types.

Another very serious problem discussed by Smelser^[G57] deals with pressure transducer degradation as a function of thermal cycling (see calibration techniques). Figure 2.1 illustrates the effect that thermal cycling can have on the transducer calibration^[G19,G57].



**BONDED STRAIN GAGE:
Range 0 - 300 psig**

Figure 2.1 Effect of thermal cycling on bonded strain gage pressure transducers.

Figure 2.1a shows the calibration of a bonded* strain gage in the "as received" condition^[G57]. The pressure transducers were initially installed into the calibration system, cooled down to the desired temperature (298, 77, or 20 K) and then pressurized while the output was monitored. Figure 2.1a illustrates that for this particular type of pressure transducer a calibration change does not occur (for one-time tests) at low temperatures; however, after the same strain gage pressure transducer has been thermal cycled from ambient down to test temperature fifty times prior to testing the effect is significant and shown in Figure 2.1b. Note that the zero-shift at 20 K not only changed appreciably, but that the calibration also changed. Another effect caused by thermal cycling not apparent from the figure was a very erratic zero-pressure output after rewarming to ambient temperature. Some transducers may be completely unacceptable for use at low temperature due to large errors resulting from hysteresis.

Figure 2.2 gives a second example of both temperature compensated and uncompensated devices. The unbonded** strain gage pressure transducer with compensation responds in quite the same manner as that shown in Figure 2.1 for the bonded type. The unbonded strain gage transducer (Figure 2.2) experienced a zero-shift like that of the bonded strain gage in Figure 2.1a before thermal cycling. This minor effect, however, can also be compensated for electronically (see section on "Strain" gage pressure transducers).

Finally as shown by the capacitive, uncompensated transducer in Figure 2.2, a severe calibration change occurs at low temperature.

* Bonded strain gage elements are generally wire in a flat grid or a thin metal foil printed and etched to produce a grid-type pattern. These gages must be cemented to the surface of a material whose strain is to be measured. Effectively, the gage then becomes a part of that surface and consequently undergoes essentially the same strain (see Figure 6.111).

** Unbonded strain gages operate basically the same as bonded ones; however, the wires are not adhered to the material as in the bonded case. Instead, the wire itself provides the mechanical link between the sensing element (diaphragm, bellows, etc.) and ground (see Figure 6.112).

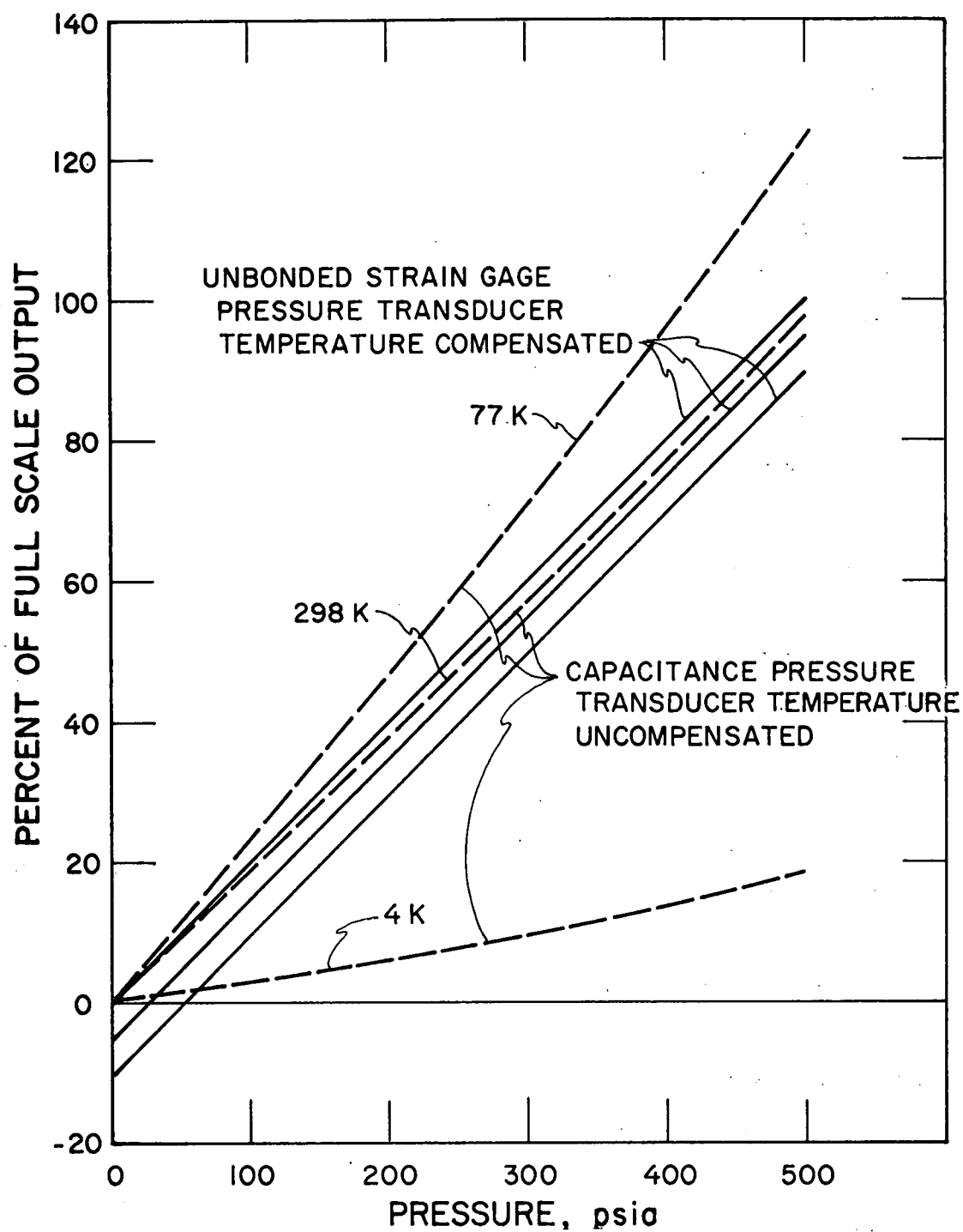


Figure 2.2 Temperature compensation and the effect on pressure transducer sensitivity.

NASA's Marshall Space Flight Center (MSFC) in Huntsville, Alabama, has routinely tested a number of pressure transducers over the last few years. The types of transducers tested include variable reluctance, capacitance, piezoelectric, potentiometric, strain gage, and linear variable differential transformer. Results of this on going program are only available in unpublished reports some of which have been made available for review.

The test program at MSFC did not always include cryogenic testing but when it did only one thermal cycle to liquid nitrogen temperature was included. Therefore, the effect of cycling can not be determined. Dean et al., [G14] have shown that in some cases after thermal cycling (approximately 50 cycles from ambient to -320°F to ambient) a more stabilized, reproducible output signal may be achieved. Therefore, when a transducer does perform satisfactorily after one thermal cycle its chance for long-term stability is greatly increased.

Unfortunately, test runs conducted at MSFC illustrate the effect of only one complete thermal cycle. For example, several transducer tests were performed at 75°F , -120°F , -320°F , and 75°F and none were re-cycled to low temperature and tested again. The summarized results of these tests are shown in Figures 2.3 to 2.5. Two pressure transducers (A&B) of the same type (model, range, etc) and from the same manufacturer are compared in the figures. The plots shown in Figures 2.3 and 2.4 show the unpredictable behavior when a transducer is subjected to low temperature. Not only does transducer output change but as shown in Figure 2.5 the device's room temperature sensitivity can be sharply altered after being exposed to cryogenic environments.

Although no tests were conducted at MSFC using ambient or cold oxygen, the effect of thermal cycling on transducers is expected to be the same as experienced in liquid nitrogen. More research and testing is necessary for a better understanding of pressure transducer behavior under adverse environmental conditions. The results shown in the figures clearly show that individual transducers even from the same manufacturer can have quite different characteristics. This fact suggests that for reasonable accuracy each

Pressure Transducer Type: Strain Gage

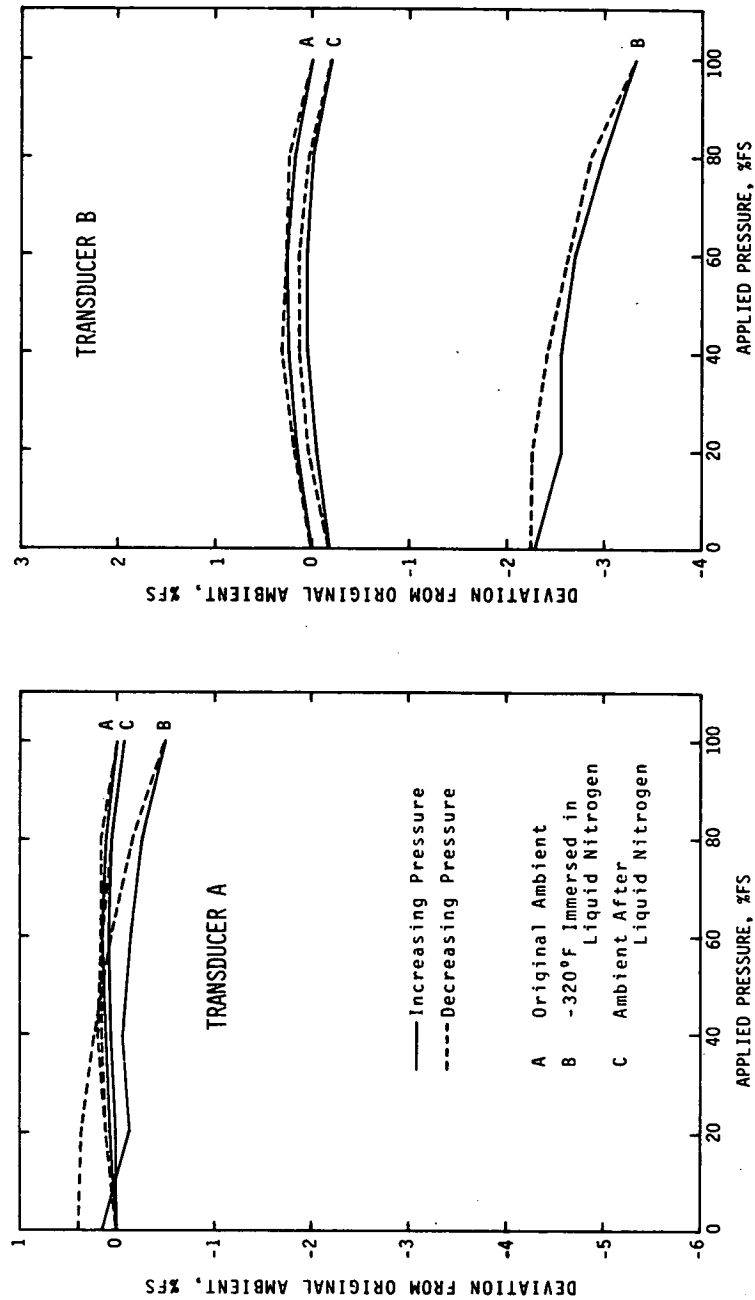


Figure 2.3 The performance characteristics of pressure transducers (same manufacturer, model, pressure range, and type)

Pressure Transducer Type: Linear Variable Differential Transformer

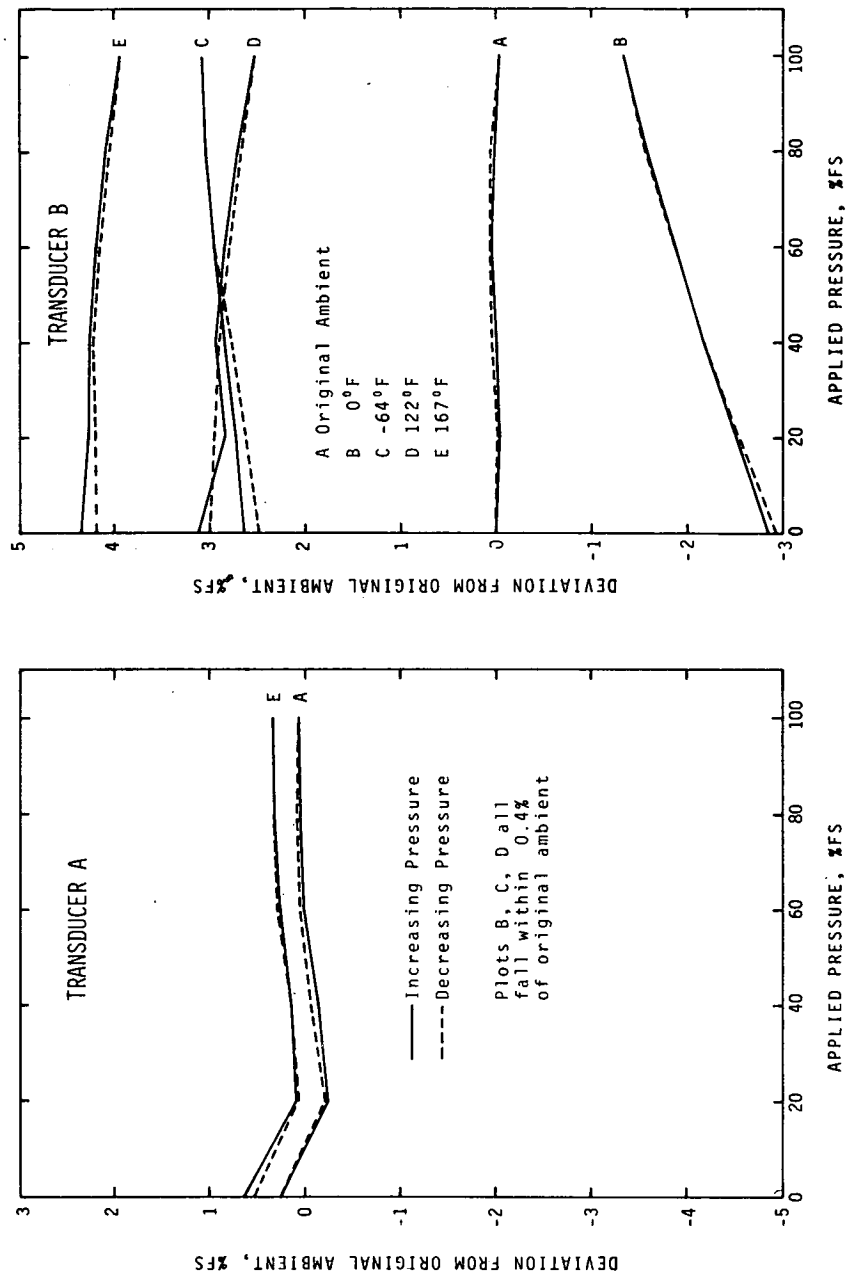


Figure 2.4 The performance characteristics of pressure transducers (same manufacturer, model, pressure range, and type)

Pressure Transducer Type: Variable Reluctance

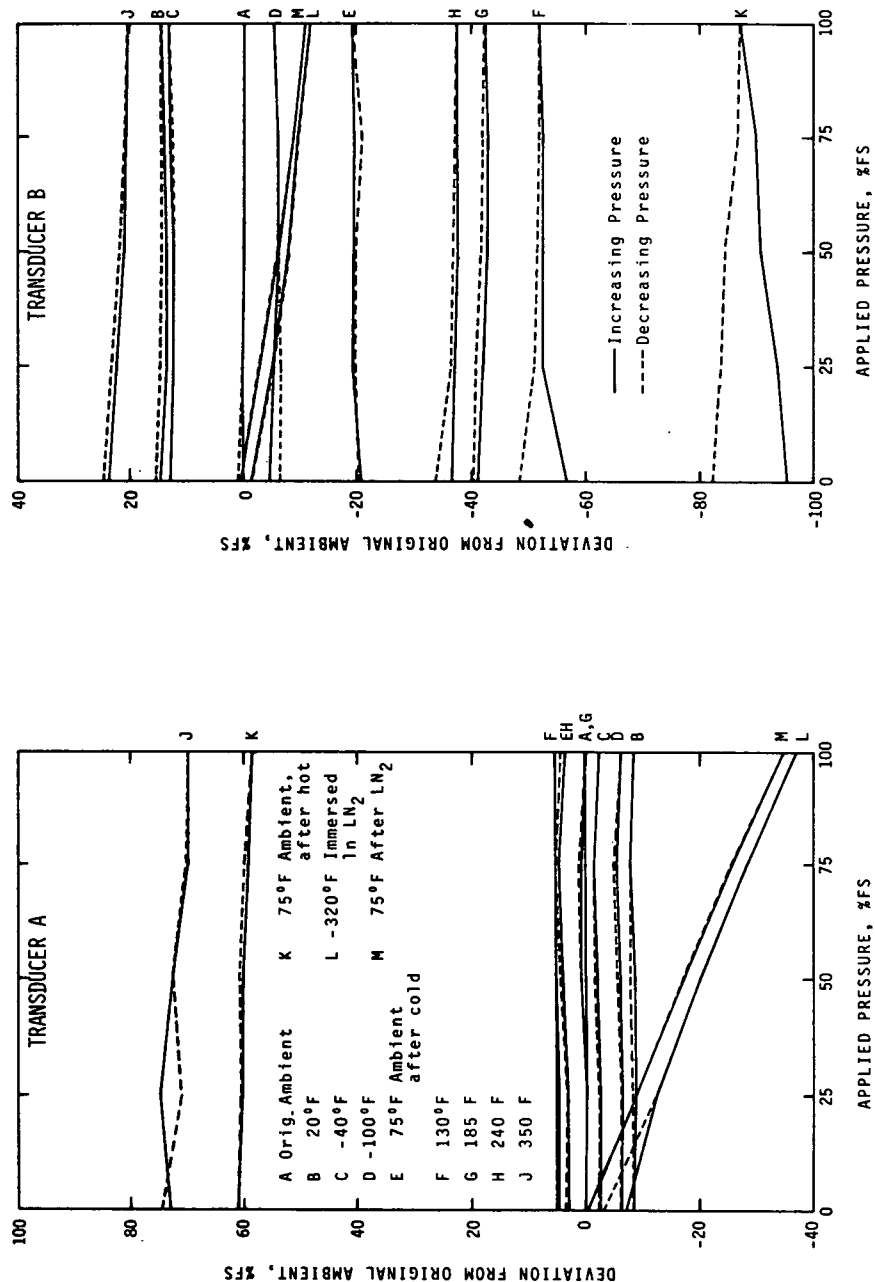


Figure 2.5 The performance characteristics of pressure transducers (same manufacturer, model, pressure range, and type)

transducer should be individually calibrated and the calibration should be done under the environmental conditions in which the transducer will be used.

In response to the needs of the National Aeronautics and Space Administration (Marshall Space Flight Center, Huntsville, Alabama) the authors are currently developing a low temperature calibration facility for static pressures to 10,000 psi with superimposed pressure fluctuations. It is hoped, this facility will allow testing and documentation of the performance of pressure transducers at cryogenic temperatures (See Recommendation Section).

3. MATERIAL COMPATIBILITY WITH GASEOUS AND LIQUID OXYGEN

When selecting instruments for pressure measurements in oxygen systems, material compatibility is extremely important, especially for high pressure measurements. A reaction can take place whenever there is a fuel, an oxidizer, and an ignition source present in a system. In a high pressure oxygen system, the oxygen is the oxidizer and the high pressure can be the source of ignition through rapid adiabatic compression. It is of paramount importance that the transducer or gage material not become the fuel in such a system.

Hust and Clark^[G49] have reviewed the literature on liquid and gaseous oxygen compatibility and have recommended the following selection procedure:

- "1. Eliminate ignition -- select a material which is least likely to ignite under operational conditions.
2. Prevent continued reaction -- select a material which tends to quench the reaction after ignition.
3. Reduce the rate of reaction -- select materials which react as slowly as possible after ignition to permit the control of the reaction."

Each system must be considered on the basis of its own unique requirements and materials selected accordingly. If only slowly varying or static pressure measurements are required, a restriction can be included at the inlet of the pressure gage to reduce the possibility of rapid compression and/or impact. In such a system high ignition temperature is probably the best criterion to use in selecting between possible materials.

If there is a possibility of impact occurring either by design or accident, then material selection must also take into account this additional source of ignition. Systems in which there is the possibility for impact include flowing streams that contain solid particles, quick opening valves, component failure, etc.

At low pressures and moderate temperatures the isentropic compression of oxygen can result in a temperature rise of over 8°R/psi. At low temperature or higher pressures the temperature rise is smaller.

There have been many tests made on the impact sensitivity of materials exposed to oxygen. Unfortunately, there is a lack of agreement about the information available from the tests. Generally speaking, the tests show that metals are more oxygen compatible than non-metals and that fluoro-carbon non-metals are generally better than the other non-metals. Of the metals, nickel alloys and copper alloys are probably slightly better than stainless steel, but all three metals are pretty good.

It is possible to obtain pressure gages and electrical pressure transducers manufactured using what appears at this time to be the most compatible materials. It is necessary to specify them, however, to ensure obtaining the proper materials. Perhaps the potentially most dangerous application involves some differential pressure transducers. Some of these devices allow at least one of the pressurant fluids to come in contact with a variety of materials within the transducer. It is necessary that all components in such a situation be of compatible material.

Hust and Clark^[G50] have prepared an unpublished report to sponsor which contains oxygen compatibility data too numerous to include in their published report^[G49]. Information from the unpublished report can be made available by Hust and Clark upon request.

4. TRANSDUCER CLEANING PROCEDURES

Even if compatible materials are used in transducers, it is necessary to have all elements in contact with liquid or gaseous oxygen free from contaminants. Probably the most common contaminant in a transducer is oil. Oil is sometimes used in manufacturing and sometimes in calibration work. Glycerol (glycerin) is also used in the testing and calibration of transducers. The physical properties of glycerol make its use as a pressure calibration fluid a distinct advantage. Before being placed in oxygen service, the transducer should be thoroughly cleaned. Volume II of this ASRDI Oxygen Technology Survey^[G51] covers cleaning requirements, procedures, and verification techniques.

Four procedures are included in [G51] relative to cleaning pressure transducers. All four procedures are repeated here (tables 4.1 - 4.4) for completeness. However, anyone working with pressure transducers should become familiar with all the information in reference [G51].

TABLE 4.1

CLEANING AND INSPECTION PROCEDURES FOR BALLISTIC MISSILE
SYSTEMS T.O. 42C-1-11 CHANGE 2, NOVEMBER 15, 1967 (REF. G52)

Transducers, Pressure Gages, and Other Dead-End Cavity Parts					
Step	Process	Agent	Time, min	Temperature °F	Remarks
1	Fill	Trichloroethylene			3/4 full and rotate component gently to circulate fluid. Repeat fill and rotate procedure two times.
2	Rinse	Petroleum ether			
3	Inspect				
4	Dry	Oven, nitrogen gas, or vacuum		180-200 140	

TABLE 4.2

CLEANING OF OXYGEN PRESSURE GAGE COMPONENTS,
NAVAL BOILER, AND TURBINE LABORATORY, MARCH 26, 1965 (REF. G53)

Step	Process	Agent	Time, min	Tempera- ture °F	Remarks
1	Disassemble				Disconnect from piping system, remove back of gage, elongate coil of capillary tubing, and open capillary tubing filing off tip.
2	Clean	Freon PCA			Forced by air pressure (5 psig) flow 150 ml of Freon PCA at approximately 50 ml/min. Repeat with two additional 124 ml portions and reverse flush with 100 ml of solvent.
3	Rinse	Freon PCA			Introduce 50 ml of solvent through connection end of gage, collect effluent in white porcelain dish, and evaporate to dryness.
4	Inspect	Ultraviolet light (3600-3900 Å)			White dish from step 3 checked for fluorescence. If fluorescence observed, continue flushing.
5	Assemble				

TABLE 4.3

CLEANING AND TESTING OF OXYGEN AND NITROGEN GAS PIPING SYSTEMS
MIL-STD-1330 (SHIPS), MAY 10, 1968 (REF. G54)

Bourdon C Tube Pressure Gages					
Step	Process	Agent	Time, min	Tempera- ture, °F	Remarks
1	Disassemble				
2	Clean	Trichlorotri-fluoroethane			MIL-C-81302 type I ultra-clean at flow rate of 50 ml/min.
3	Check	Ultraviolet light (3600-3900Å)			Continue flushing if fluorescence is evident.
4	Dry	Dry, oil-free nitrogen			

TABLE 4.4
CLEANING METHODS AND PROCESSES, NASA FRC PROCESS
SPECIFICATION 20-1, NOVEMBER 1, 1970 (REF. G55)

Specific Cleaning Process for Pressure Transducers and Bourdon Tubes					
Step	Process	Agent	Time, min	Temperature, °F	Remarks
1	Preclean	Trichloro-ethylene			Hot solvent.
2	Clean	Trichloro-ethylene	1 1	180±5 Ambient	Soak in hot solvent. Place in ambient solvent. Repeat cycle 10 times. Ambient solvent not to exceed 85°F.
3	Dry	Oven	150 150	250±10 180±10	For Bourdon tubes. For pressure transducers.

The cleaning procedure in practice at NASA Lewis Research Center involves exposure of the pressure cavity to a cleaning solution to remove any hydrocarbon, removal of the cleaning solution with a more volatile solvent and drying with inert nitrogen gas.

A typical programmed cycle is as follows:

1. Transducers evacuated for 5 minutes to about 50 microns.
2. Trichloroethane (NA500) is sprayed into transducer.
3. Trichloroethane is released and transducers evacuated for 5 minutes.
4. Spray and evacuation is performed 5 times ending with a 6-minute evacuation to 50 microns.
5. Trichlorotrifluoroethane (FREON, NASA Spec. No. 237A) is sprayed into transducer, released and evacuated for 5 minutes to 50 microns.
6. Rinse sequence (No. 5) repeated 5 times ending with 6-minute evacuation.
7. Evacuation broken with dry nitrogen gas.
8. Transducers capped and sealed in plastic bag.

5. PRESSURE TAP CONNECTIONS

Making accurate pressure measurements depends not only on instrument selection, but also on properly designed tap geometry, interconnecting line size, and location.

When making measurements where a liquid-gas interface will occur, as in a liquid oxygen differential pressure liquid-level gage, the location of the pressure tap line is very important. The problem of pulsations in pressure tap lines where a vapor-liquid interface can occur has been discussed in section 2.

It is usually preferable to connect the pressure-measuring instrument as close to the system as possible. This reduces the problem of loss of response caused by damping in the pressure tap lines. Where maximum dynamic response is important, a diaphragm transducer mounted directly at the point of measurement should be used whenever possible. Figure 5.1a shows a typical installation.

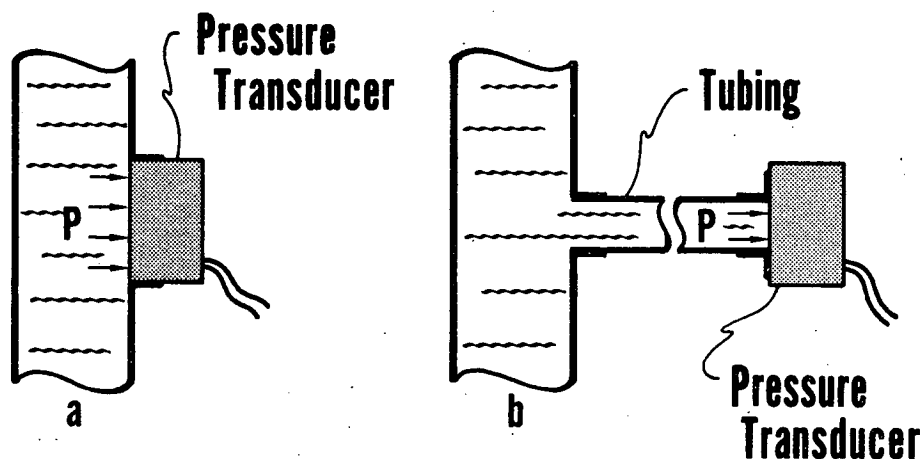


Figure 5.1 Transducer Locations

There are many applications where the instrument must be located some distance from the system; therefore, the interconnecting line becomes an important part of the measuring instrumentation. In dynamic systems where frequency response is important and the transducer cannot be mounted at the system, the interconnecting line should be large. ASME^[G2] recommends 1/2 in. pipe for these installations and 1/4 in. O.D. tubing where dynamic affects are not important. Figure 5.1b shows a typical installation. In either case the length of the line should be as short as possible. In most applications a compromise must be made on the line size, particularly when cryogenic oxygen is in the system in which the pressure is being measured. Large line sizes may introduce intolerably high heat leak into the system and may even change the local pressure being measured. The requirement to keep the instruments in a warm environment may require long pressure tap lines also. Hord^[G48] has developed some simplified equations for predicting the response to step inputs in pneumatic systems. His analysis covers the three flow regimes of free molecular, transition, and continuum. Hord defines the flow regimes as:

Free molecular flow ($K_n \geq 0.5$)

Continuum (viscous) flow ($K_n \leq 0.005$).

The mean free path (in cm) is given by

$$\lambda = 8.6 (\mu/P) (T/M)^{1/2}$$

where μ is in poise, P is in torr, and T is in Kelvins. A summary of the applications of Hord's equations is given in table 5.1 and the equations follow the table. These equations can be used to calculate the time required for 66-2/3% of a step change in pressure to be measured at the transducer.

TABLE 5.1

Summary of Formulas

Application	Equation
Step size is limited by the computational precision desired by the user where viscous flow occurs and not limited in the molecular flow range: Kn need not be considered except to establish applicable flow range and thus the allowable step size. Best estimates for all steps which submit to the assumptions of this analysis ($Re < 2 \times 10^3$, $Ma < 0.33$ for viscous flow).	(1)
Good estimates for very small steps (pressure ratio > 0.9) where viscous flow occurs. Step size is not limited in the molecular flow range. Kn may be disregarded after allowable step size is determined ($Re < 2 \times 10^3$, $Ma < 0.33$ for viscous flow).	(2)
Best estimates for continuum flow ($C_{pf} \gg C_{fm}$): step size is restricted by $Ma < 0.33$ and $Re < 2 \times 10^3$.	(3)
Best estimates for free molecule flow ($C_{fm} \gg C_{pf}$): step size is unlimited.	(4)

$$TRF = \frac{L}{0.87C_a} \left(\frac{V'}{2 kP_o + C_{fm}} \right)$$

$$\ln \left\{ \frac{(1-n) [k(P_o + P_{si}) + C_{fm}]}{k[(P_o + P_{si}) + n(P_o - P_{si})] + C_{fm}} \right\} \quad (1)$$

$$TRF = \frac{L}{0.76C_a} - \left(\frac{V'}{2 kP_o + C_{fm}} \right) \ln(1-n) \quad (2)$$

$$(TRF)_{pf} \approx \frac{L}{0.87C_a} + \frac{V'}{2 P_o} \ln \left[\frac{P_o \frac{1+n}{1-n} + P_{si}}{P_o + P_{si}} \right], P_o \neq 0 \quad (3)$$

$$\tau_{fm} \approx - \frac{V'}{C_{fm}} \ln(1-n) \quad (4)$$

Where:

Kn	= Knudsen number ($\equiv \lambda/D$)
λ	= Mean free path of gas
μ	= viscosity
P	= absolute pressure
T	= absolute temperature
M	= molecular weight
D	= Inside diameter of transmitting tube
Re	= Reynolds number
Ma	= Mach number (\equiv gas velocity/acoustic velocity)
C_{pf}	= Tube conductance in the viscous (Poiseuille) flow regime [$\equiv (\pi/128) (D^4/L) (\bar{P}/\mu)$]
\bar{P}	= Arithmetic mean pressure in the transmitting tube
h	= Viscosity defined in terms of force [typical units are $\text{lb}_f \cdot \text{s}/\text{ft}^2$]
TRF	= A time-response function which predicts the time required for a physical system to attain a fraction of the applied step input.
L	= Effective length of transmitting tubing
C_a	= Adiabatic acoustic velocity in gas in free space
V'	= Apparent volume of pressure-measuring system (\equiv transducer volume + 0.5 tubing volume)
k	= Term in flow equation, treated as constant [$\equiv (\pi/128) (D^4/26\mu)$]
P_o	= Absolute pressure of fluid at open end of tubing
C_{fm}	= Tube conductance in the free molecule flow regime [$\equiv (D^3/6L) (2\pi RT)^{1/2}$]
n	= A fraction of the applied pressure step, commonly taken as $1-1/e=0.632$
P_{si}	= Absolute pressure of fluid at the sensor when time zero
τ_{fm}	= Time constant [the time constant is defined as the amplitude-invariant parameter of a physical system which predicts the time required for the system to attain $(1-1/e)$ of an applied step perturbation; the time-dependent behavior of the system must be describable by a first order, linear, ordinary differential equation with constant coefficients]

Each installation will require a critical analysis and decisions made on the best overall combination taking into account the required frequency response, heat leak, instrument environmental requirements, etc.

In a dynamic system the pressure tap hole must be made with a great deal of care. ASME^[G2] recommends that the diameter of the pressure tap hole be as small as practicable but not exceed 1/16 in. The length of the hole should be 2-1/2 times the tap hole diameter. The edge of the hole must be free of burrs and be square. Rayle^[G47] has experimentally determined the effect of hole size and configuration on pressure measurement errors. Figure 5.2 shows the effect of hole diameter, and figure 5.3 shows the effect of several different possible hole configurations. The errors shown are percent of dynamic head. It can be readily seen from these figures that in high velocity flow, poor pressure tap fabrication can lead to very large errors. Rayle also determined that a burr on the edge of the hole can cause errors of 15 to 20 percent of the dynamic head. Rayle suggests that "sharp edge holes can best be produced by removing the burr in three or four steps, alternately working at the tap wall and the main bore wall, finishing with a final smoothing of the main bore."

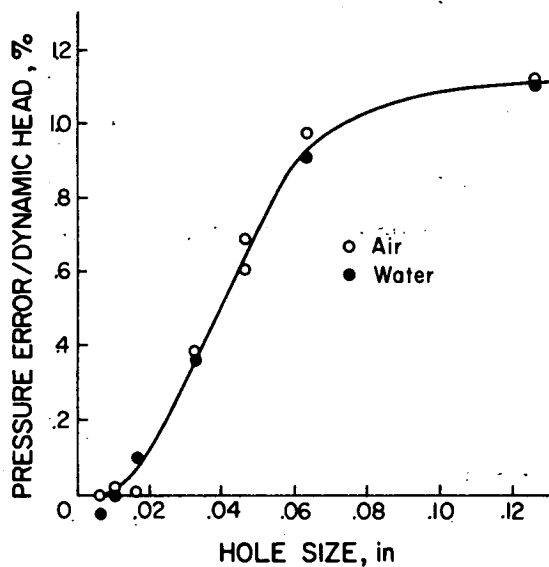


Figure 5.2 Pressure taps and the effect of hole size.

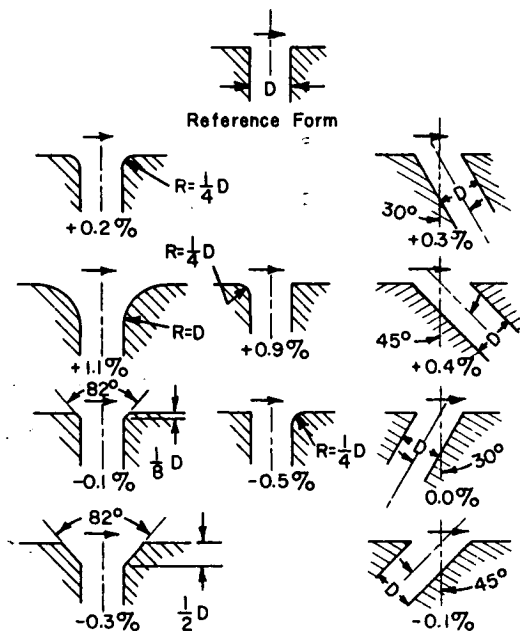


Figure 5.3 Pressure taps and the effect of hole geometry.

6. TRANSDUCER TYPES AND DESCRIPTION

6.1 MANOMETERS

Manometers measure pressure by the balance of a column of liquid. Since the density and height of the liquid column can be determined very accurately, the manometer has become known as a primary standard pressure gage. This type of instrument can be used to measure gage (including vacuum), differential, atmospheric, or absolute pressure.

The most commonly used liquids for manometers are mercury and water since they are readily available and their physical properties are known. Other liquids are also used such as carbon tetrachloride and tetrabromoethane. They all have in common low vapor pressures, insolubility, and other favorable properties.

The densities (at 20°C) for manometer fluids are listed below^[G2].

Table 6.11 Manometer Fluid Densities

	<u>g cm⁻³*</u>
Water	1.000
Carbon tetrachloride	1.594
Tetrabromo-ethane	2.953
Mercury	13.543

Four popular manometer systems and governing equations are schematically shown in Figures 6.11 - 6.14. Others such as the ring-balance, liquid-sealed bell (absolute and differential type), and the double-bell differential manometer, etc., are not shown but are in limited use.

* g cm⁻³ = 0.03613 lb in⁻³.

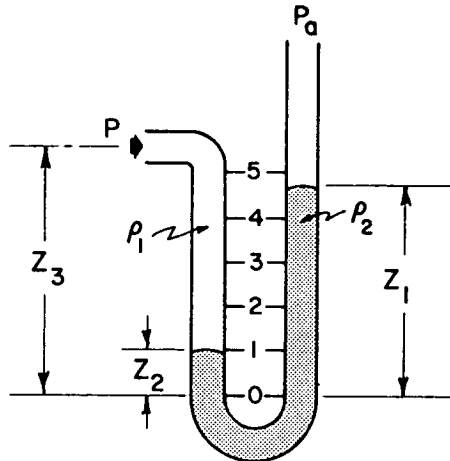


Figure 6.11 U-tube.

$$P + g\rho_1 (z_3 - z_2) + g\rho_2 z_2 = P_a + g\rho_2 z_1$$

or

$$P = P_a + g\rho_2 (z_1 - z_2) - g\rho_1 (z_3 - z_2) \quad (\text{U-Tube})$$

where

- P = fluid pressure in pipe, Pa
- ρ_1 = density of the pipe fluid at the temperature of the manometer connection, Kg m^{-3}
- ρ_2 = density of the manometric liquid, Kg m^{-3}
- P_a = atmospheric pressure, Pa
- g = acceleration of gravity, ms^{-2}

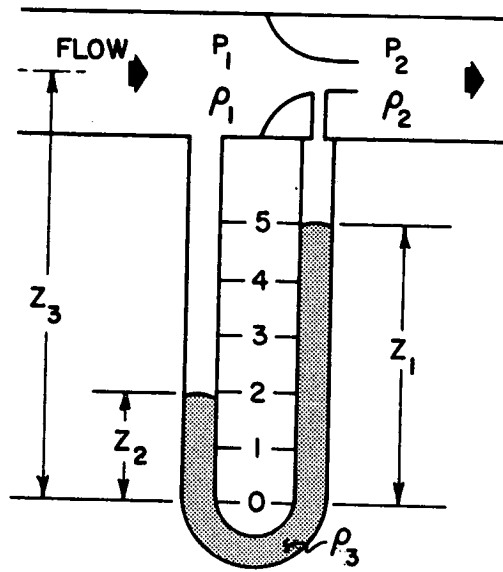


Figure 6.12 Differential.

$$\begin{aligned}
 P_1 + (z_3 - z_2) \rho_1 g + z_2 \rho_3 g \\
 = P_2 + (z_3 - z_1) \rho_2 g + z_1 \rho_3 g
 \end{aligned}$$

or

$$P_1 - P_2 = (z_1 - z_2) \rho_3 g + (z_3 - z_1) \rho_2 g - (z_3 - z_2) \rho_1 g$$

If $(\rho_2 - \rho_1)(z_3 - z_1)$ is small compared with $(\rho_3 - \rho_1)(z_2 - z_1)$, then

$$P = P_1 - P_2 \cong g(z_1 - z_2)(\rho_3 - \rho_1) \text{ (Differential Manometer)}$$

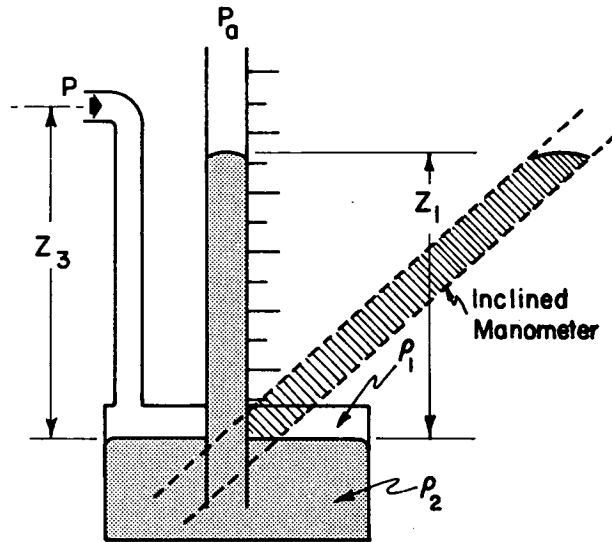


Figure 6.13 Cistern.

$$P = P_a + Z_1 g \rho_2 - Z_3 g \rho_1 \quad (\text{Cistern Manometer})$$

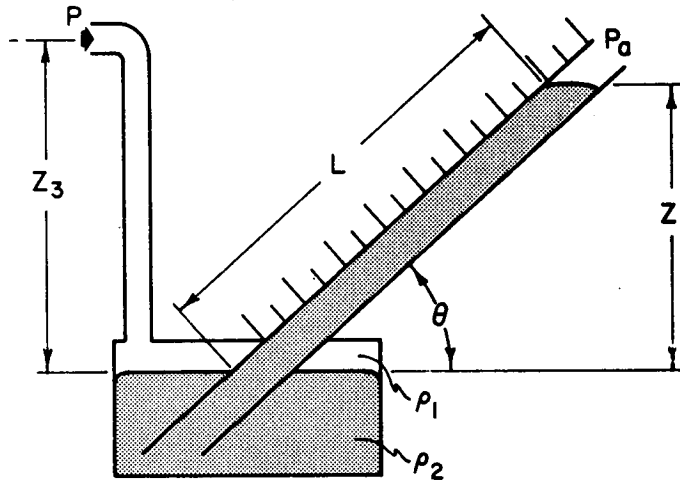


Figure 6.14 Inclined.

or for an inclined manometer

$$P = P_a + Z_1 g \rho_2 - Z_3 g \rho_1$$

since

$$Z_1 = L \sin \theta$$

$$P = P_a + \rho_2 g L \sin \theta - Z_3 \rho_1 g \quad (\text{Inclined Manometer})$$

To obtain reproducible results it is necessary that the manometer fluid be precision clean. If precautionary measures such as those described in references Ma8, Mall, and Ma13 are followed, the initial calibration will remain essentially unchanged for months. The meniscus with its problem of adhesion to the manometer tube is accentuated as the ratio of liquid surface to volume increases [Ma9, Mall]. It is therefore desirable to minimize the total effect by using large-bore manometer tubes [G2]. For example, the capillary error for a 4 mm tube using mercury is approximately 2 mm and is reduced by a factor of ten if the bore is increased from 4 to 12 mm. For tubes of approximately 1.27 cm or larger effects of capillarity are insignificant. Before making a reading from any liquid manometer, it is always advisable to tap the column first. This will allow the meniscus to reach a position of least distortion in the column. It is therefore quite often that vibration in a manometer system is helpful.

Correction for deviation from standard temperature and gravity must be made in a system since these quantities are directly proportional to the height of the fluid column. Also, if the uncertainty in pressure measurement for a mercury manometer should be held to 0.01 percent, the mercury temperature must be known within $\pm 0.6^\circ\text{C}$ [Ma13].

Table 6.12 lists the boiling point (C) and vapor pressure (mm Hg @ 20C) for some fluids commonly found in liquid manometers [G1].

Table 6.12 Boiling point and vapor pressure of some manometer fluids.

Liquid	Boiling point, °C	Vapor pressure at 20°C, mm Hg
Carbon tetrachloride	76	91
Ethyl alcohol	78	43.9
n-Octane	126	10.5
m-Xylene	138	6.4
Fluid A 1.0 viscosity grade	152	2.6
Mercury	357	0.0012

MANOMETER SPECIFICATIONS

Types of pressure measurement:

Gage (including vacuum), absolute or differential

Pressure ranges:

10-500 in H_2O (differential manometer)

5-50 in Hg (U-type absolute-pressure gage)

0.5-50 in H_2O (inclined-tube manometer)

6-130 in of liquid (manometer well)

Resolution:

With optimum viewing conditions as to illumination and sharpness of the meniscus, sighting by eye is probably not better than 0.025 mm (0.001 in.).

[Ma9, Ma13]

Accuracy:

"If the uncertainty in pressure measurement is to be held to 0.01 percent (0.1 millibar @ 1 atm) the mercury temperature must be known within $\pm 0.6^\circ C_1$ and proportionately smaller for better accuracy." [Ma13]

Temperature (range, compensation, and stability):

Must be corrected for liquid used. See tables in reference Ma13.

Calibration:

A primary means for calibrating other devices.

Vibration effects:

Small vibrations have no effect.

Materials:

Tubes are most often glass, but some manometers use copper, brass, or stainless steel tubes.

Oxygen usage:

Manometers can be used with gaseous or liquid oxygen providing the fluid chosen is not reactive with the system being measured (e.g., an oil filled manometer would be totally unacceptable). Another suggestion may be to use an intermediate fluid which is inert to both the system and manometer liquid.

Advantages:

1. May be used for highly accurate measurements over a small pressure range or for less accurate measurements over a wide pressure range.
2. Sensitivity may be changed easily by altering the amount of fluid in the manometer.
3. Operation is not affected by vibration.
4. Easy to calibrate.
5. Relatively inexpensive.
6. Ease of fabrication.

Disadvantages:

1. Surface tension of manometer fluid creates a capillary effect and possible hysteresis.
2. An accurate means for determining meniscus height must be used for improved accuracy.
3. Manometer fluid must be chosen such that it does not react with the system being measured (for use with oxygen service, oil filled manometers are unacceptable).

6.2 BOURDON TUBE

The Bourdon tube gage and manometer are the two most prevalent gage types in use today. The design and fabrication of such a device, utilizing the Bourdon tube principle, involve a relatively small number of considerations, most of which are familiar to designers. The mathematical relationships between design considerations, however, can be extremely complex. Typical examples of basic Bourdon tube design are shown below in Figure 6.21.

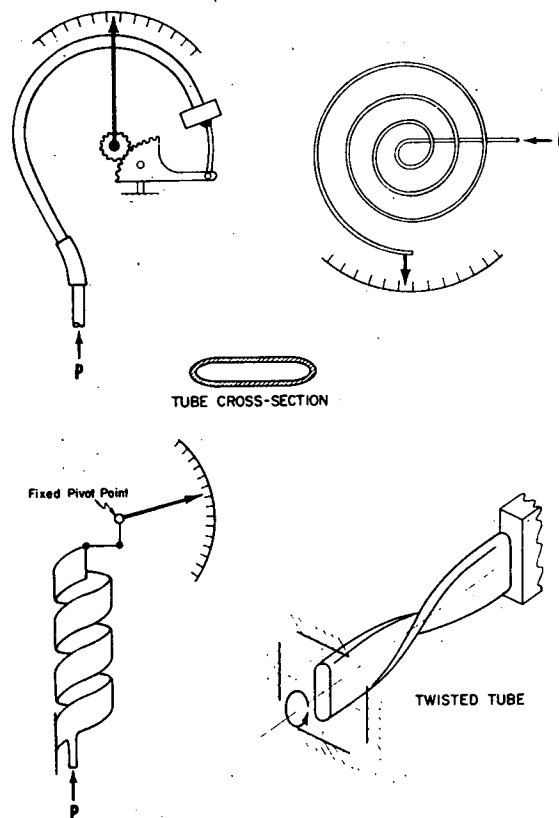


Figure 6.21 Bourdon tube configurations.

The following equations are given to describe Bourdon tubes (helical, circular and C-type) and the effects of pressure, torque, elevation, and temperature. Since there are presently no reliable analytical mathematical models to describe Bourdon tubes, the following equations, which have been empirically derived, must be used.

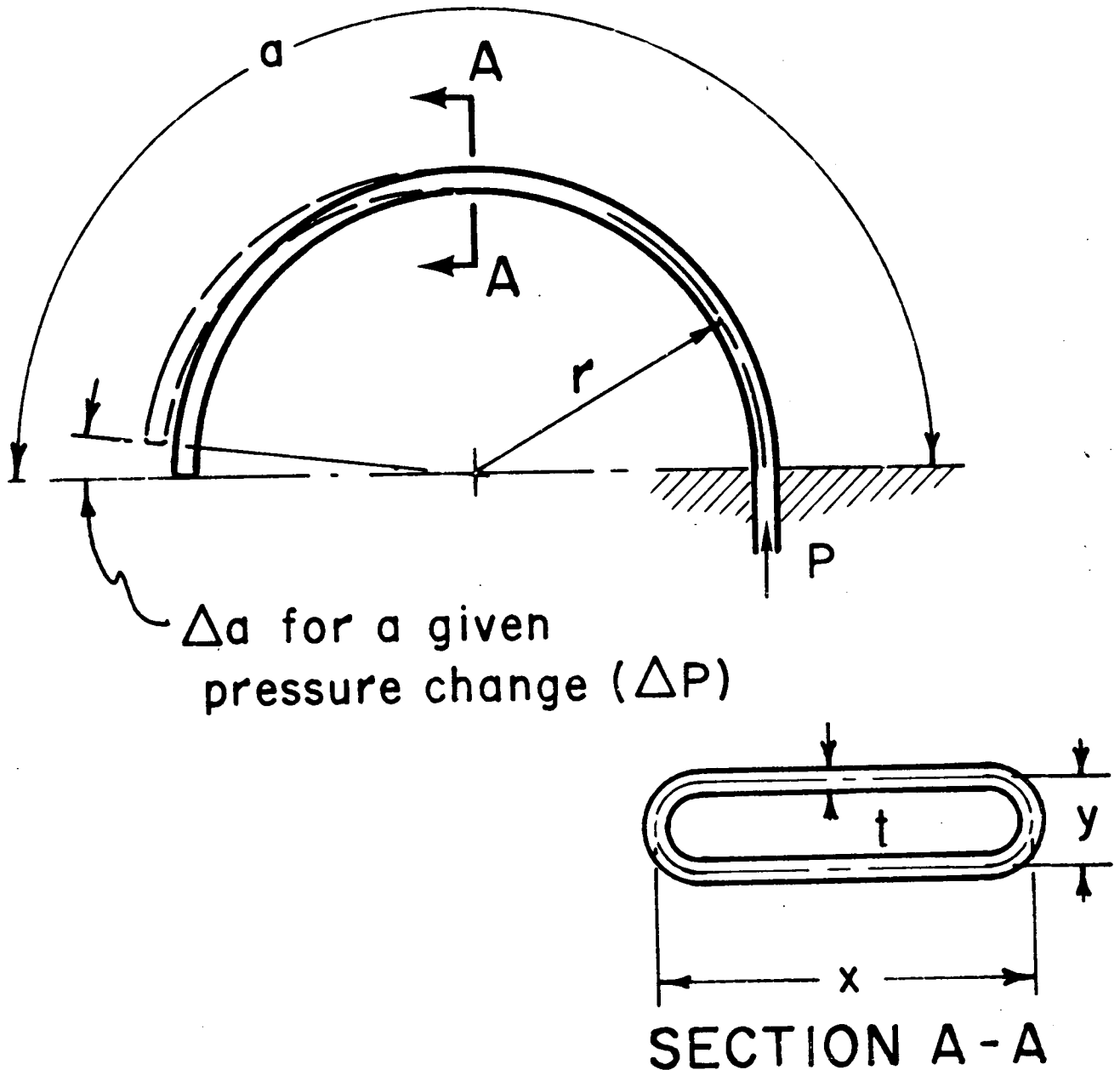


Figure 6.22 C-type bourdon tube geometry.

The deflection of a Bourdon tube is given by^[G1]

$$\Delta a = K \frac{aP}{E} f \left[\left(\frac{r}{t} \right)^a \left(\frac{x}{y} \right)^b \left(\frac{x}{t} \right)^c \right]$$

where

- Δa = Deflection of element tip, deg
- K = Empirical constant
- a = Total angle subtended by Bourdon tube before pressurization, deg.
- P = Pressure difference between inside and outside of tube, psi
- E = Modulus of elasticity
- x, y = Cross-sectional length and width of tube, in.
- t = Thickness of tube, in.
- r = Element radius of curvature (C-type elements $r = \text{const.}$
Spiral type elements $r = \text{variable}$).

By conducting tests on a number of Bourdon tubes it was found that

$$\Delta a = K \frac{aP}{E} \left(\frac{r}{t} \right)^a \left(\frac{x}{y} \right)^b \left(\frac{x}{t} \right)^c$$

The constants K , a , b , and c are found by laboratory tests on elements.

For a flat cross-sectional tube (as shown in Fig. 6.22) the following equation was determined.

$$\Delta a = 0.05 \frac{aP}{E} \left(\frac{r}{t} \right)^{0.20} \left(\frac{x}{y} \right)^{0.33} \left(\frac{x}{t} \right)^{3.00}$$

The power rating of a Bourdon element (which is useful for mechanism design) is given by

$$W = FD$$

- where F = Force acting on element tip, parallel to direction of motion.
- D = Displacement of tip, parallel to motion, in.
- W = Power factor of element.

Ordinarily, Bourdon elements sense gage pressure and variation in atmospheric pressure is not a factor. However, when absolute pressure is desired, the error due to pressure change is

$$E = \frac{P_a}{P_m} 100$$

where

E = percent error

P_a = atmospheric pressure change (from reference pressure)

P_m = maximum pressure span of device.

If the pressure device is located above or below the point of measurement, an elevation error must be taken into consideration.

$$E = \frac{H\rho}{P_m} 100$$

where

E = percent error

H = height between measuring element and point of measurement

ρ = density of fluid in pipe

P_m = maximum pressure span of device.

Also, ambient temperature change will cause an error which is

$$E = 0.02 \Delta T \frac{P}{P_m}$$

where

E = percent error

ΔT = temperature change (from reference temperature)

P = pressure applied to tube

P_m = maximum pressure span of device.

In the above case, temperature compensation may be accomplished utilizing a bimetal strip.

The material chosen to fabricate a Bourdon tube will relate to the instrument's sensitivity, range, accuracy and precision. Some of those used are^[G1]:

Group I (strain-hardened alloys)

- 1) Cartridge brass (70 Cu - 30 Zn)
- 2) Trumpet brass (80 Cu - 20 Zn)
- 3) Phosphor bronze
- 4) Silicon bronze
- 5) Austenitic stainless steel
(AISI Types 304 and 316)

Group II (Precipitation-hardened alloys)

- 1) Beryllium copper

Group III (Heat-treated alloys-quenched and drawn)

- 1) Low-alloy steels
- 2) Martensitic stainless steel (AISI Type 403).

The C-type Bourdon tube (shown in Figure 6.22) is oval and curved through an arc of approximately 200-300 degrees^[Bo3]. Fused quartz is also being used for helical Bourdon tubes. Fabricated from this material the instrument has less hysteresis, creep, and relaxation than any other material known.

Bourdon gages are used in making pressure (including vacuum), compound, and differential-pressure measurements. If the case of the gage is pressurized (for differential measurements) a clean transparent gas or fluid must be used to permit readability of the dial and prevent deterioration of gears and bearings. An alternate form of differential-pressure gage uses two Bourdon tubes arranged such that the motion of one subtracts from the other.

The Bourdon tube is a special type of cantilever spring and the path of the tip deflection is also similar. Mathematical models for cantilevered springs have also been used for Bourdon tubes with good agreement. A typical mechanical arrangement most commonly used for Bourdon tube devices is shown in Figure 6.21.

Another more complicated and versatile system illustrated in Figure 6.23, is used primarily in conjunction with a recorder and may be in the form of a spirial or helix. The optical transducer shown uses a helical Bourdon tube providing high sensitivity, resolution, and repeatability. In operation, the deflection of the pressurized (P) tube goes through an angle θ and is followed by the photocell until the microammeter is nulled. In this zero position the digital counter reading is multiplied by a scale factor to determine the pressure. In some instances, for the gages mentioned, an absolute pressure measurement can be made by evacuation of the capsule external to the Bourdon tube.

Another application of the Bourdon tube to detect pressure utilizes a potentiometric transducer. A device of this type is coupled to a Bourdon tube via mechanical linkage, and as the system is stressed, the tip deflects causing the potentiometer to change position. This produces a change in resistance which varies as a function of the applied pressure. The advantage of this arrangement allows for remote pressure monitoring.

Bourdon gages can be used at high pressures (to approx. 100,000 psi) and with flammable gases or liquids. Therefore, gage safety should be considered in the event of rupture^[Bo4]. Gage types from several manufacturers range from those with no safety features to those with hinged blowout backs and specific mounting instructions.

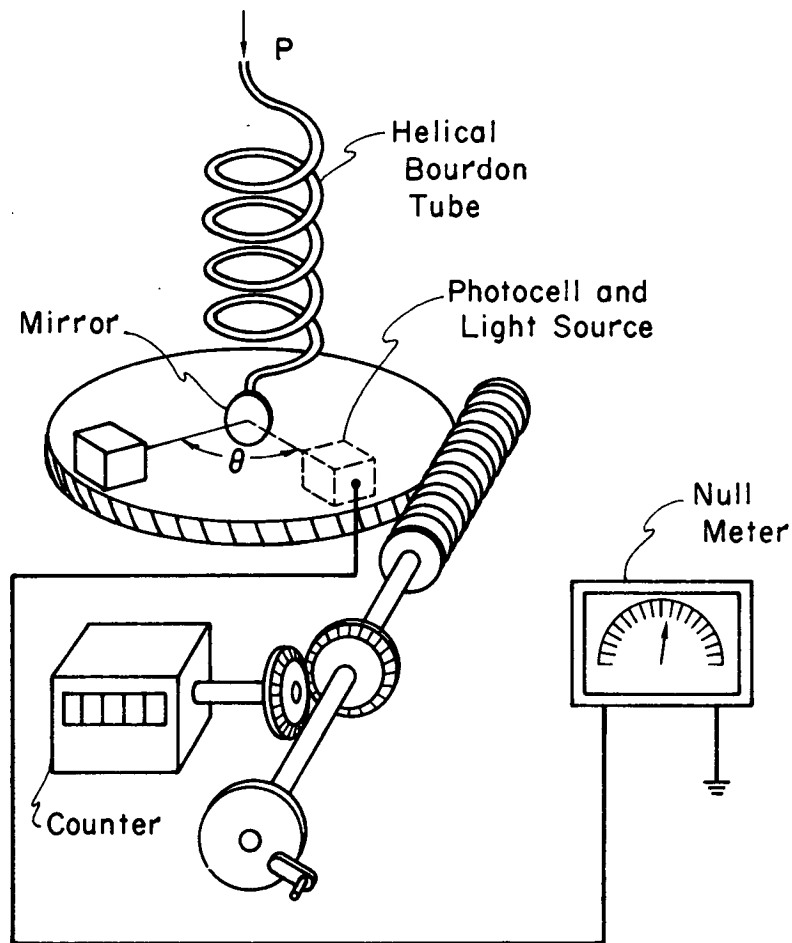


Figure 6.23 Optical pressure transducer utilizing a helical bourdon tube.

BOURDON TUBE SPECIFICATIONS

Types of pressure measurement:

Gage (including vacuum), absolute or differential.

Pressure ranges:

C-Bourdon -- 12 to 100,000 psi

Helical Bourdon -- 12 to 80,000 psi

Spiral Bourdon -- 12 to 10,000 psi

The vacuum range 0-30 in. Hg is also available for the C-Bourdon type.

Resolution:

Reading can usually be resolved to within one-quarter of one percent of full scale.

Accuracy:

$\pm 1/2$ to ± 1 percent of full span.

Temperature (range, compensation, and stability):

Maximum operating temperature is 200°F.

Maximum uncompensated ambient temperature errors for $\pm 25^\circ\text{F}$ change is $\pm 1/4$ percent of full span.

Calibration:

Straightforward using a deadweight tester.

Vibration effects:

Insensitive. In fact, most vibrations are helpful in overcoming the friction in a Bourdon system. On the otherhand, if the vibrations are excessive, accelerated wear will take place.

Materials:

Strain-hardened alloys include:

- 1) cartridge brass
- 2) Trumpet brass
- 3) Phosphor bronze
- 4) Silicon bronze
- 5) austenitic stainless steel (AISI Types 304 and 316).

Materials (continued):

Precipitation hardened alloys include:

- 1) Beryllium copper

Heat-treated alloys - quenched and drawn include:

- 1) Low-alloy steels
- 2) Martensitic stainless steels (AISI Type 403).

Oxygen usage:

Gaseous O_2 -yes; liquid O_2 -no (for the case where the liquid would come in direct contact with the gage). The Bourdon tube and linkages should always be at room temperature.

Installation requirements and limitations:

Gages should be installed vertically in a position where the temperature is, as nearly as possible, 68°F.

In case of gages with pipes filled with liquid, it is often more convenient to have the gage pipe connection installed at a definite level with respect to apparatus in test, in order to simplify or eliminate the correction for liquid in pipes for pressure measurement.

Remarks:

This type of gage is generally not used for pressure monitoring remotely. Also, the gage is bulky which puts limitations on the installation.

Advantages:

1. Simple mechanism.
2. Several pressure ranges available.
3. Costly electronics are not required.
4. Can be used to make or break electrical contacts, tip toggle switches, or drive self-synchronous meters for remote-reading indicators.
5. Also used with strain, capacitance, magnetic, and other electrical systems.

Disadvantages:

1. Space limitations.
2. Limited pressure range.
3. Power or energy to operate related mechanism must be supplied by the tube.
4. Friction (rolling or sliding friction results in a system lag).
5. Slow response to pressure changes.
6. Inherent hysteresis.

6.3 DIAPHRAGM

Diaphragm-type gages are most often used to measure low-pressure (including vacuum) from ranges of 0 to 0.2 in water and 0 to 30 psi. Diaphragm gages are used to measure low-pressure absolute, draft, liquid-level, and differential. Some applications require that the diaphragm element be able to withstand high pressures and remain within its elastic limit. Such a diaphragm might be fabricated from a full hard, cold-rolled nickel, chromium, or iron alloy, which can have an elastic limit above 80,000 psi and be used to 800°F^[D1].

The three most common types of diaphragms are shown in Figure 6.31.

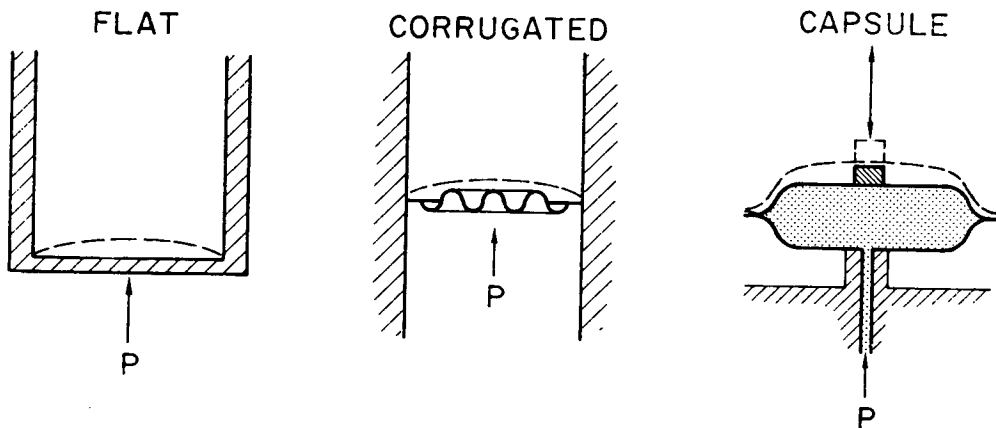


Figure 6.31 Basic diaphragm types.

Many gages use diaphragms in conjunction with other methods for measuring pressure. That is, a diaphragm may be used as a force-summing device and coupled to a resistance strain gage, capacitive system, or LVDT (linear variable differential transformer). Devices such as these will be covered in other sections. Only diaphragm gages which are mechanically coupled to an indicator for pressure measurement will be covered. The pressure gage shown in Figure 6.32 is a typical example of how most diaphragms operate.

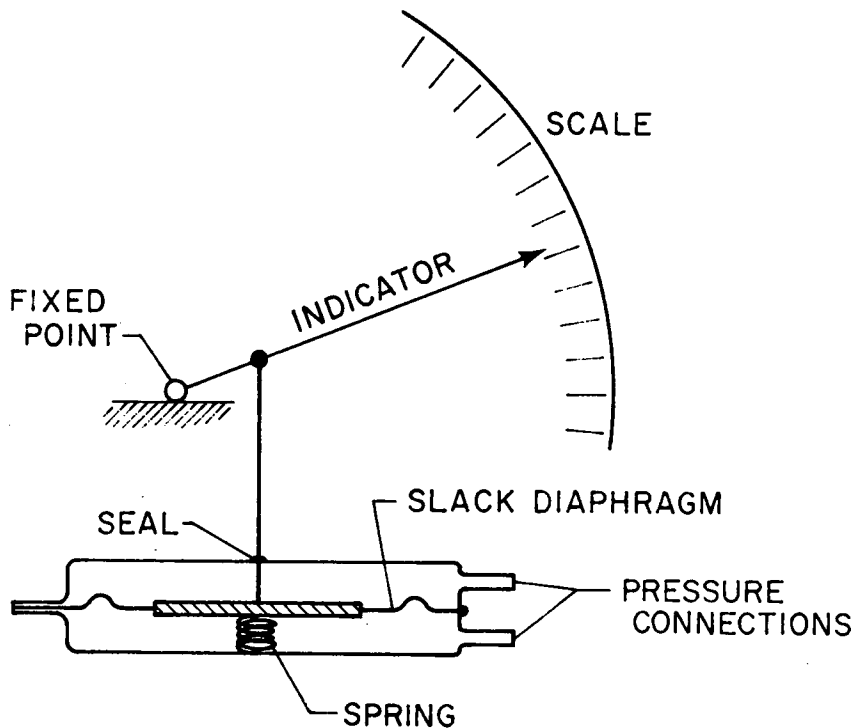


Figure 6.32 Slack diaphragm pressure gage.

A gage may use single or multiple diaphragms depending on the sensitivity required or gage type.

Diaphragms are fabricated from an extensive list of materials which include trumpet brass, phosphor bronze, beryllium copper, stainless steels, and some plastics. The geometry is usually in the form of a thin disc or shell (two discs bonded peripherally by soldering, welding or brazing).

Some important factors which determine the deflectional properties of a diaphragm are: (1) diameter of the disc or shell, (2) metal thickness, (3) number of shell corrugations and their shape, (4) applied pressure, and (5) modulus of elasticity.

Diaphragms, if designed improperly, can be very non-linear with respect to the pressure-deflection relationship. Equations relating these parameters are given later and should be helpful. With proper material selection, it is possible to obtain good linearity over a wide range, a minimum of hysteresis, and no permanent zero shift.

Pressure fluctuations will not have an adverse effect on the gage if consideration has been given in the design stage. A diaphragm must not have natural frequencies which may coincide with those of the system being measured. To avoid this, the following equation is used to calculate the natural frequency (N) of a circular diaphragm^[Ca7]:

$$N = 0.4745 \frac{t}{r^2} \left[\frac{E}{\rho (1-\sigma^2)} \right]^{1/2}$$

where

- t = Diaphragm thickness, cm
- r = Diaphragm radius, cm
- ρ = Material density, g cm⁻³
- E = Young's modulus, g cm⁻²
- σ = Poisson's ratio

Example:

For mild steel, $E = 2.0 \times 10^{12}$, $\rho = 7.8$, and $\sigma = 0.28$. For a diaphragm of 2.54 cm diameter and 0.0635 cm thickness the natural frequency is

$$N = 0.4745 \frac{0.0635}{(1.27)^2} \left[\frac{2.0 \times 10^{12}}{7.8 (1-0.28^2)} \right]^{1/2}$$
$$N = 9.853 \times 10^3 \text{ Hz}$$

with higher harmonics occurring at $2N$, $4N$, etc.

A diaphragm gage may be fabricated using either a single disc or pair of discs peripherally joined to form a capsule. Multiple capsules may also be combined in a single gage for greater displacements. Factors governing the choice are gage sensitivity and total displacement needed (range). The following two formulae give the relationship between pressure and deflection of diaphragms (disc and corrugated capsule). For most materials the full-scale deflection of a diaphragm must be less than one-third the diaphragm thickness to insure a non-linearity of less than 5 percent.

The pressure-deflection equation for a flat diaphragm (with edges clamped) is^[G3]

$$P = \frac{16Et^4}{3r^4(1-\mu^2)} \left[\frac{d}{t} + 0.488 \left(\frac{d}{t} \right)^3 \right]$$

where

- P = Pressure difference across diaphragm, psi
- E = Young's modulus, psi
- t = Diaphragm thickness, in
- μ = Poisson's ratio
- r = Active diaphragm radius, in
- d = Deflection at center of diaphragm, in

If one designs to maintain linearity at less than 5 percent the term $(\frac{d}{t})^3$ is negligible compared with $(\frac{d}{t})$. The pressure deflection equation then reduces to

$$P = \frac{16Et^4d}{3r^4t(1-\mu^2)}$$

or

$$d = 0.1875 \frac{Pr^4(1-\mu^2)}{Et^3} .$$

The pressure-deflection relationship for a corrugated capsule diaphragm is given by the following equation^[G1]:

$$d = KN(P-P_O)D^x t^{-y}$$

where

- P = Applied pressure, psig
- P_O = Initial pressure, psig
- K = Capsule constant including Young's modulus of elasticity and corrugation design (see Table 6.31)
- t = Diaphragm shell thickness, in
- D = Active diameter of diaphragm shell, in
- d = Deflection at center of capsule, in
- N = Number of capsules
- x,y = exponent constants

A formula which has been found satisfactory for a capsule of common design is

$$d = KN(P-P_O)t^{-1.5}D^4 .$$

It must be noted from the above equation that the diaphragm deflection is dependent on the diameter to the fourth power. Or, for the same pressure

change and doubling the diameter, an increased diaphragm deflection of sixteen times may be obtained.

The values of E and K are listed below for some commonly used diaphragm materials.

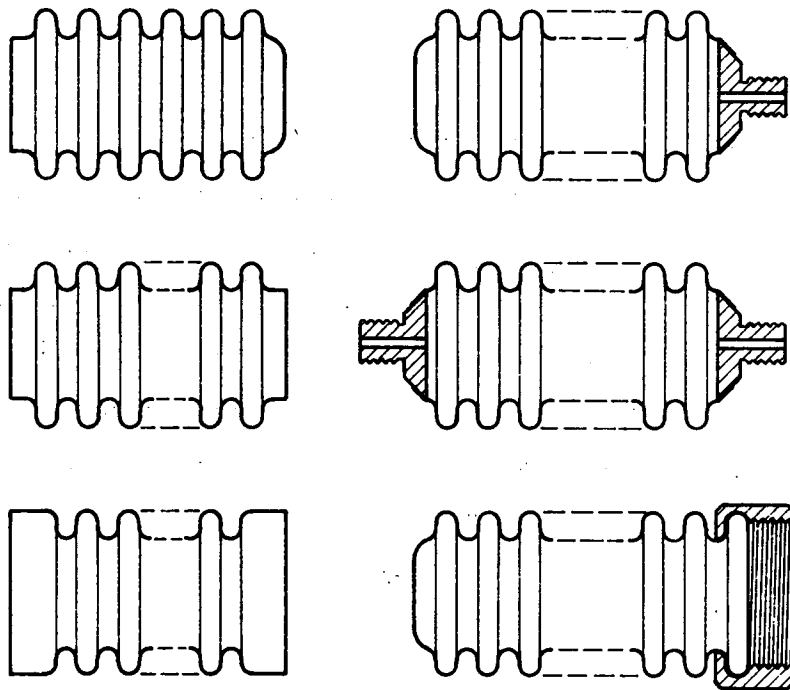
Table 6.31 E and K values for commonly used materials.

Material	E,psi	Capsule Constant K
Phosphor bronze	16×10^6	0.24×10^{-6}
Beryllium copper	20×10^6	0.19×10^{-6}
Type 316 stainless steel	28×10^6	0.14×10^{-6}

6.4 BELLOWS

The bellows pressure gage, like the Bourdon tube and diaphragm, is a force-summing device and is quite often used in conjunction with other electrical principles (capacitive, strain gage, etc.) to measure pressures. The details of such electrical principles will be found in another section.

The bellows is a one-piece longitudinally expansive and contractive device usually fabricated into the geometry shown in Figure 6.41 from thin-walled seamless tubing. The process is carried out either mechanically or hydraulically with bellows sizes ranging from 0.80 cm to 30 cm in diameter and generally have several folds or convolutions. The figure also shows several common types of bellows and methods of attaching end fittings^[G1].



COMMON TYPES OF BELLOWS AND
FITTING ATTACHMENT METHODS

Figure 6.41 Common types of bellows and fitting attachment methods.

Trumpet brass, stainless steels, phosphor bronze, and beryllium copper are among the most popular materials chosen for bellows fabrication. Material selection is generally based on the corrosiveness of the bellows environment and, secondly, the sensitivity required.

Bellows gages are low pressure measuring devices such as the diaphragm gages. They can measure gage pressure (including vacuum), differential, absolute, and compound. The arrangement shown in Figure 6.42 illustrates how the bellows can be installed in a gage for differential pressure measurement. P_2 may also be vented to the atmosphere for gage pressure measurements.

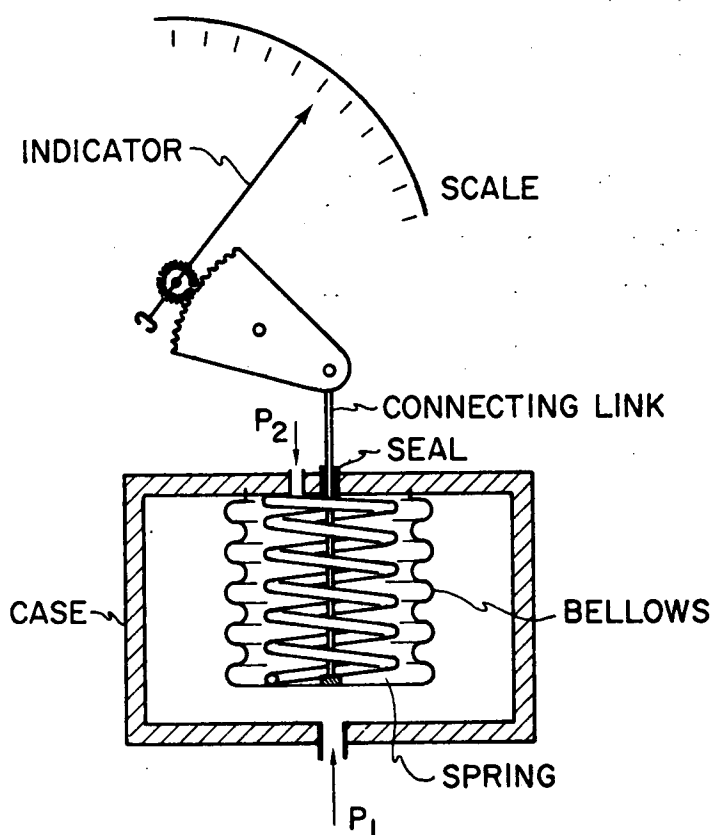


Figure 6.42 Bellows gage for measuring differential pressure.

As with other elastic member elements (Bourdon tube and diaphragm) the bellows follow Hook's law which states, within the elastic limit, that stress is proportional to strain; or in other words, the displacement of the bellows is proportional to the applied pressure. A volumetric change can arise as the bellows temperature changes, and therefore, a second bellows is sometimes used to compensate for this effect (see Figure 6.43).

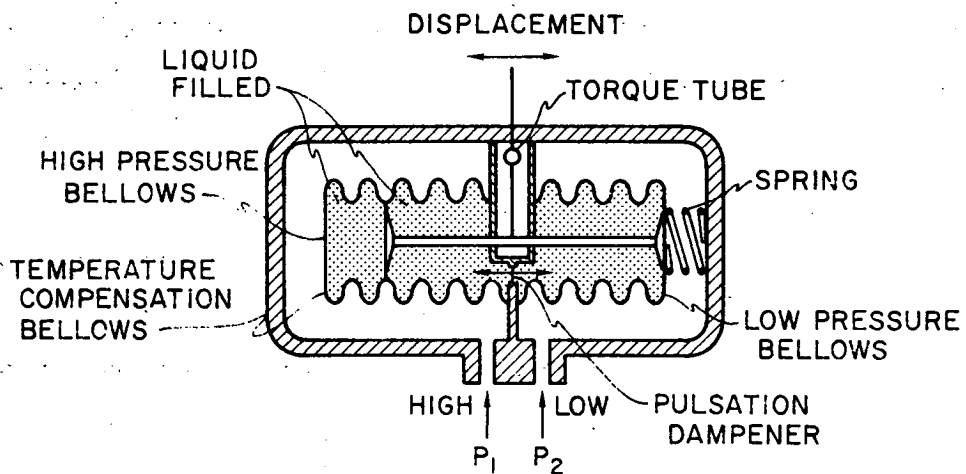


Figure 6.43 Temperature compensated differential pressure bellows gage.

Figure 6.43 not only shows how temperature compensation is made, but also how bellows can be used in pairs for differential measurement. The one illustrated is designed for low-differential-pressure measurement of high static pressure. Both bellows, including the one for temperature compensation, are liquid filled. As high pressure enters the unit (P_2), the bellows contract and the liquid is transmitted to the low-pressure bellows via the connecting passage (with its rate controlled by a pulsation dampener). The resulting motion to an indicator is made through the use of a pressure-tight torque tube. A liquid with a low coefficient of thermal expansion such as a solution of ethylene glycol and water should be used. Other features such as overrange and over-pressure protection may be incorporated into this design.

The following table will be helpful in determining the characteristics of a single-ply brass bellows^[G1]. This table covers only a few of the many sizes available. Also, the maximum stroke stated should not be used in combination with the maximum pressure stated.



Table 6. 41 Characteristics of single-ply brass bellows.

A, outside diam., in.	B, inside diam., in.	Max number of active convolutions	Approx length per active convolution, in.	Effective area, sq. in., or linear volume, cu in.	Max stroke per active convolution, in.	Spring rate per active convolution lb/in.	Stroke per active convolution, in. per psi pressure	Max pressure psi
15/32	5/16	18	0.045	0.12	0.0067	600	0.0002	315
9/16	23/64	24	0.045	0.16	0.0044	685	0.00023	235
3/4	1/2	26	0.057	0.31	0.0128	480	0.00065	165
1 1/64	5/8	11	0.091	0.53	0.0285	125	0.00424	55
1 1/2	63/64	14	0.151	1.2	0.0293	825	0.00146	170
2	1 23/64	15	0.141	2.22	0.0405	346	0.0064	60
2 7/16	1 37/64	12	0.195	3.18	0.0517	528	0.00603	70
2 15/16	2 9/64	17	0.164	5.07	0.055	388	0.0131	50
4 3/64	3 1/16	16	0.19	9.92	0.1025	168	0.0592	20
5 7/8	4 15/16	10	0.231	23.0	0.0872	300	0.0769	20
8 7/8	7 57/64	14	0.22	55.5	0.0409	1,218	0.0449	25
12	10 13/16	10	0.225	102.4	0.0676	530	0.198	10
Notes regarding use of table		Available in any number of active convolutions up to number given above	Multiply by number of active convolutions to obtain normal free length of active portion of bellows	0.1963 (A + B) ² expressed as cubic inches is approximate volume per inch length of active portion of bellows	Multiply by number of active convolutions to obtain maximum stroke of active portion of bellows	Divide by number of active convolutions to obtain spring rate of active portion of bellows	Multiply by number of active convolutions to obtain flexibility of active portion of bellows	Do not use with maximum stroke. See Fig. 18, Life-expectancy Chart

The deflection equation for a spring-opposed bellows is given by

$$d = P \frac{A_e}{K_b + K_s}$$

where

d = Deflection of bellows, in.

P = Applied pressure, psi.

A_e = Effective area of bellows, in².*

K_b = Force constant of bellows lb in⁻¹.

K_s = Force constant of restraining spring lb in⁻¹.

Solving the equation for P ,

$$P = \frac{d(K_b + K_s)}{A_e}$$

Now, if the bellows assembly must operate an electric switch or some other mechanism, the equation must reflect this additional force required.

The equation now becomes

$$P = \frac{F + d_s(K_b + K_s)}{A_e}$$

where

F = Force required to actuate the switch or mechanism, lb.

d_s = Deflection required to operate the switch or mechanism, in.

* The effective area of bellows is calculated by

$$A_e = \pi b^2 \left[1 + \frac{c^4 + 3 - 4c^2 (1 + \log_e c) + \frac{16c^2}{c^2 - 1} (\log_e c)}{(c^2 - 1) + \frac{16c^2}{c^2 - 1} (\log_e c)^2} \right]$$

where

c = A/B (see Table 6.41).

Bellows, if properly designed for, can be cycled for long periods of time without failure. The graph given in Figure 6.44 will help the designer to attain maximum life from a set of bellows; as shown if displacement and pressure can be kept minimal, the expectant bellows life can be well over 1.0×10^8 cycles. It is advantageous to restrict the bellows displacement is a linear function of pressure and is not for displacements greater than 10 percent [G12].

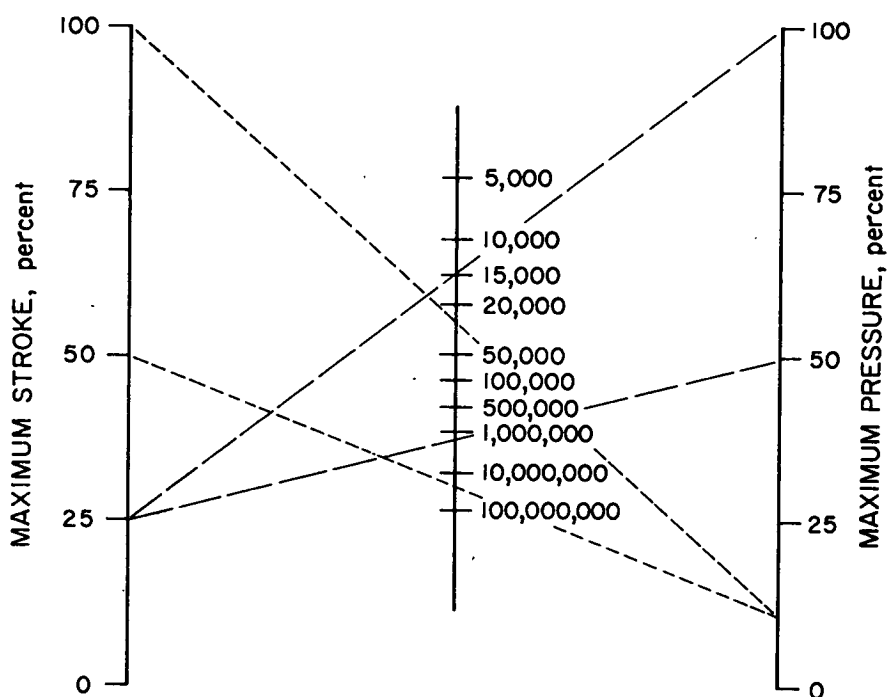


Figure 6.44 Cyclic life of bellows.

Beryllium copper is an excellent material for the construction of bellows, since in the annealed condition its properties approach those of copper. This allowed for fabrication without damage to the material. After forming, a heat-treatment for 3 hours at 275°C produced an overall effect for every point on the bellows resulting in a tensile strength of 150,000 to 180,000 psi. In general, the elastic properties of beryllium copper bellows, fabricated in the above manner, are quite superior to those of other nonferrous materials.

A bellows, especially one which is long in proportion to its diameter, becomes unstable and tends to buckle when pressure is applied internally and a load is applied to one end, since each convolution tries to increase in length. For applications where a long bellows is necessary, a better design is to apply the pressure externally so that each convolution tends to shorten and exert a pull upon adjacent convolutions, thus keeping the bellows straight.

6.5 STRAIN

Strain gages of two basic types, either bonded or unbonded, are used in devices to measure pressure. In both cases however, the principle is the same. As a wire is elastically stretched, its length and diameter are altered, resulting in a change in its electrical resistance. By using this basic principle and a force-summing device such as a diaphragm, bellows, or bourdon tube, the displacement of an elastically strained wire will be proportional to the change in electrical resistance and, thereby, the pressure.

Poisson's ratio is a characteristic of every metal and is given by $\mu = (dr/r)/(dL/L)$. The volume of a wire is given by the formula $V = \pi r^2 L$ where

r = Radius of wire.

L = Length of segment.

If we let $dV = 0$ and differentiate the volume equation, we find that Poisson's Ratio = -0.5. Actually, Poisson's Ratio for most metals is between -0.25 and -0.30 indicating that dV is not equal to zero and that a decrease of density occurs with tensile stress.

The gage factor (GF) relates the strain to which a wire has been subjected, to a change of resistance. Or ^[G1],

$$GF = \frac{\Delta R/R}{\Delta L/L}$$

where

ΔR = Change in gage resistance.

R = Original gage resistance.

ΔL = Change in gage length.

L = Original gage length.

Gage factors vary from one type of resistance wire to the next, but the factor of a given wire is the same whether the gage is used in tension or compression. For most commonly used strain gage materials, gage factors range from 2.0 to 5.0. High gage factor materials tend to be more sensitive

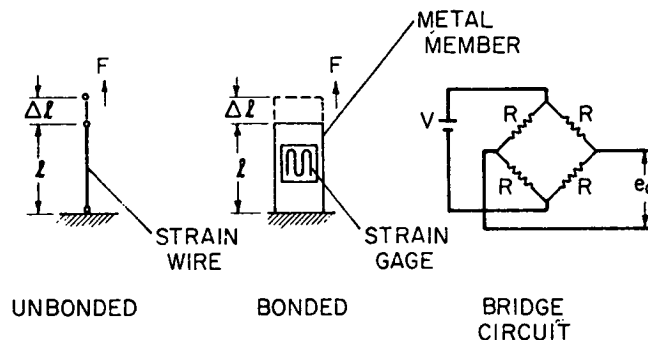
to temperature and less stable than low gage factor materials (see Table 6.51) [G14].

Table 6.51 Gage factor and temperature coefficient for some strain gage materials.

Strain wire Composition	Gage factor $(\Delta R/R) / (\Delta L/L)$	Temperature coefficient of resistance
80 Ni, 20 Cr	2.0	high
4 Ni, 12 Mn, 84 Cu	0.47	very low
45 Ni, 55 Cu	2.0	negligible
36 Ni, 8 Cr, 0.5 Mo	3.5	high
Ni	-12.1	unstable

The most popular strain wire used is 4 Ni, 12 Mn, 84 Cu, but its poor temperature coefficient limits its use.

Figure 6.51 shows both types of strain gages, bonded and unbonded, and a simplified schematic of the bridge circuit used in both cases. One or more legs in the Wheatstone bridge circuit may be active depending on sensitivity or compensation required.



$$\frac{e_o}{V} = \frac{N}{4} \frac{\Delta R}{R}$$

N = NUMBER OF ACTIVE LEGS

$$GF = \frac{\Delta R/R}{\Delta L/L}$$

Figure 6.51 Bonded and unbonded strain gages and associated circuitry.

The bonded strain gage is usually cemented to a metal beam, tube, diaphragm or other strain sensing element. The adhesion process must be done carefully and steps taken to insure that all parts of the thin film gage are bonded to the sensing element.

The active strain wire (approximately 1 to 1-1/2 mils) is doped to a sheet of ceramic, paper, or plastic for ease in handling and is removed once the wire is cemented to the sensing element. There are also strain gages which have been embedded in thin films of plastic and are epoxied to the sensing element as a unit. Many different types of strain gages are available with resistance values ranging from 60 to 5,000 ohms and effective gage lengths from 1/16 to 6 in. The basic standard gage is approximately 120 ohms and passes 25 ma of current in a 6-volt bridge circuit.

To select the proper gage for a specific application, several factors must first be considered. The following is a list of these considerations^[G1]:

- 1) Gage factor, maximum.
- 2) Resistance per unit length, maximum.
- 3) Temperature coefficient of resistance, minimum.
- 4) Coefficient of linear expansion, minimum*.
- 5) Melting point, maximum.
- 6) Thermoelectric tendency at connection, minimum.
- 7) Optimum flexibility, ease of soldering, and negligible hysteresis for complete cycle.

As stated above, it is very important to bond the strain gage to the sensing member permanently. For use in long-duration applications to 300°F, a phenolic resin bonded and baked in place is recommended. Commercial strain gages are generally guaranteed to within ± 1 percent of the stated gage-factor value and have a resistance tolerance of ± 0.25 percent of the nominal value.

* For cryogenic applications it is advisable to select a gage with an expansivity close to that of the sensing element to maintain the bond during cooling.

Unbonded strain gages operate basically the same as bonded ones; however, the wires do not adhere to any sensing element as such. The resistance wire itself provides the mechanical link between the sensing element and ground. Then, as the diaphragm (or whatever sensing element used) is deflected, the strain wires are stretched. The general arrangement for an unbonded strain sensing system incorporates a stationary frame that supports a moveable armature. Between the moveable armature and frame are wraps of tensioned strain gage wire which change resistance as the armature is displaced (see Figure 6.52).

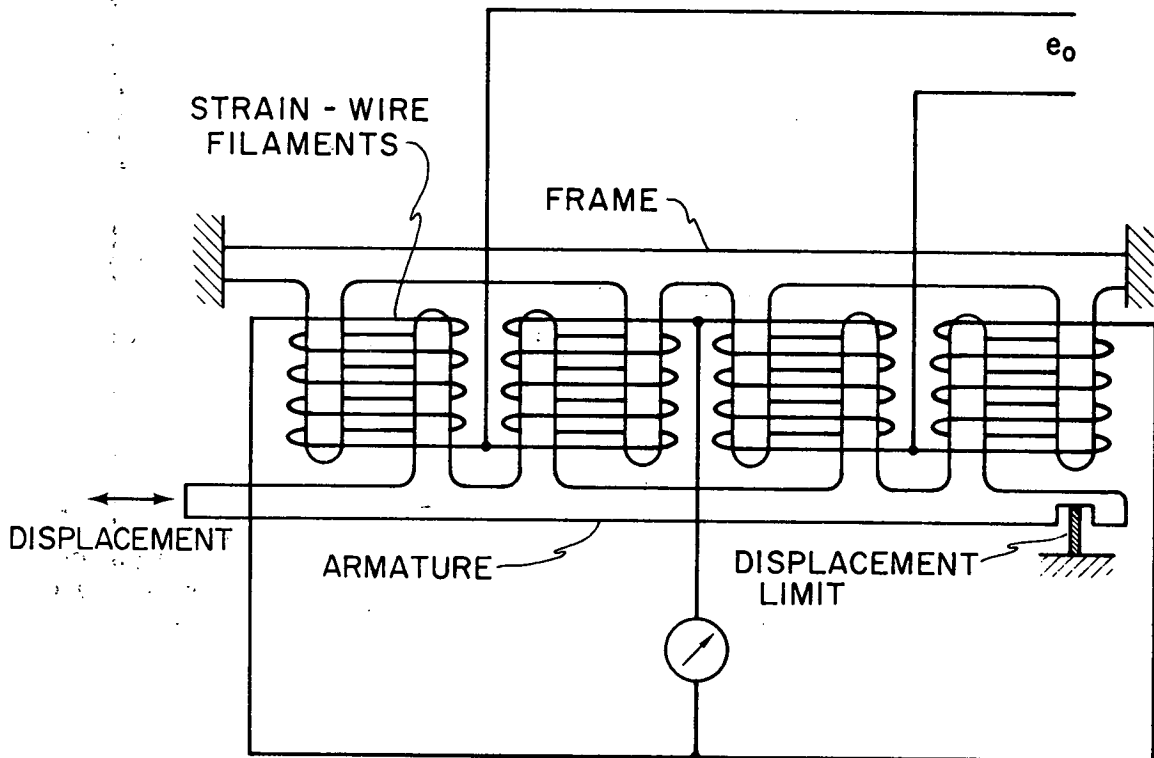


Figure 6.52 Typical unbonded strain gage installation.

When all four arms of the Wheatstone bridge circuit are active, special mounting for inactive gages is not necessary. The advantages of using four active strain gages in the bridge circuit are increased output, high sensitivity and reading accuracy. It is extremely important, however, to compensate the circuit for temperature changes since small changes produce spurious readings if all four arms of the bridge are not effected alike. Figure 6.53 illustrates the total circuitry including elements necessary for calibration and temperature compensation.

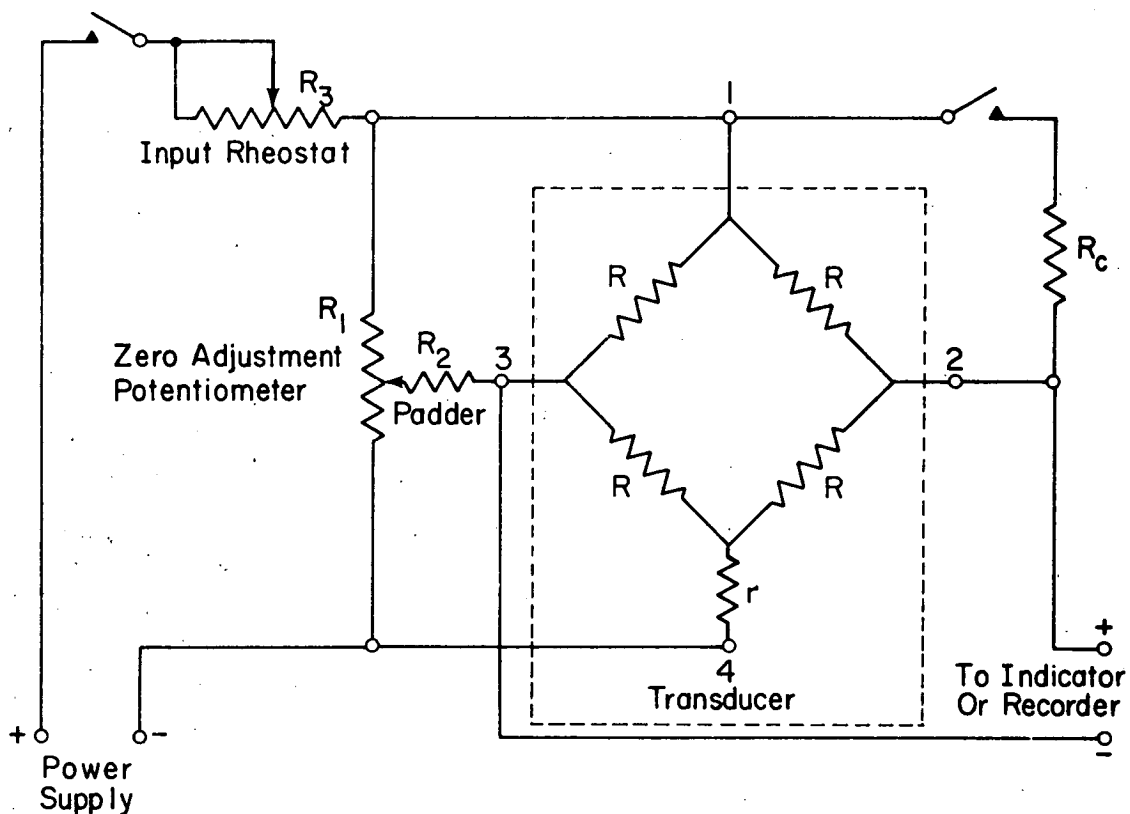


Figure 6.53 Electrical circuitry necessary for bonded or unbonded strain gage pressure transducer.

A voltage may be held constant across the input to the pressure transducer with the addition of a positive resistor (r)*. This will cause the calibration factor (F) to remain constant by decreasing input current for an increased operating temperature. "The voltage on the transducer at $T = 0$ is $VR/(R + r_0)$ and at temperature T is $VR/(R + r)$.

The ratio by which it changes is $(R + r_0)/(R + r)$.

This fraction must correct for the variation of F, or

$$F_0(1 + cT)(R + r_0)/[R + r_0(1 + aT)] = \text{Const.}$$

or

$$(1 + cT)/(R + r_0 + r_0aT) = \text{Constant} = \\ (1 + cT)/\{(R + r_0)[1 + r_0aT/(r_0 + r)]\}.$$

For this fraction to be constant,

$$C = (r_0a)/(R + r_0), \text{ or } r_0 = (cR)/(a-c)$$

where

F = Calibration factor ($\mu\text{V}/\text{V}/\text{psig}$ or g)

r = $r_0(1 + aT)$

a = Temperature difference from reference

c = Temperature coefficient of the calibration factor F,
so that $F = F_0(1 + cT)$

V_g = Actual voltage on transducer

R = Bridge resistance

Note that the compensating resistor must be at the same temperature as the transducer and preferably should be inside it^[G15].

The compensating resistor should also remain, with minimal heat loss, thermally stable and at equilibrium with the transducer.

* "The series input resistance may be split into two equal portions, one on each side of the bridge. With this arrangement, temperature errors are reduced in the calibrating resistor method of circuit standardization"^[G15]

Resistor R_c shown in Figure 6.53 is for the purpose of calibration^[G10].

The behavior of an unbonded, temperature compensated, strain gage pressure transducer is shown in Figure 2.2 ("Cryogenic Pressure Measurement")^[G19,G57]. For direct comparison, an uncompensated capacitance pressure transducer is shown on the same plot. In each case the capacitive pressure transducer was rezeroed prior to testing at another temperature and the result was a severe change in sensitivity, indicating the need for compensation. The zero-shift exhibited by the compensated strain gage pressure transducer can be simply taken care of by the addition of a resistor into the zero adjustment circuit (see Ref. G10,G15).

Table 6.52 will also be helpful in making the decision as to which method of strain measurement should be used (Bourdon, bellows, etc.).

Table 6.52 Characteristics of pressure transducers using strain gages.

Sensing elements	Type strain gage	Available ranges psi	Accuracy, % full range	Temperature limit, °F	Natural frequency, cps
Bourdon tube and bellows	Bonded	0-10 to 0-50,000	$\pm 1/4$	250	300 to 2,000
Bellows and diaphragm	Unbonded	0-0.05 to 0-10,000	$\pm 1/2$	-65 to +250	270 to 10,000
Bellows and cantilever beam	Bonded	0-10 to 0-2,500	$\pm 1/4$		
Ring type	Bonded	0-25 to 0-10,000	± 1	-50 to +170	Above 1,500
Diaphragms	Bonded	-15-100 to -15-10,000	± 1	-300 to 6000°F. High-air or water cooling supplied	To 45,000

*All entries are suitable for a-c or d-c operation.

Advantages:

1. High accuracy.
2. Minimal change due to temperature differences. System may also be temperature compensated.
3. Can measure both static and dynamic pressures. For static measurements a stable high gain direct coupled amplifier is needed.
4. May be energized by ac or dc.
5. Low sensitivity to shock and vibration.
6. Continuous and practically infinite resolution.
7. Gage and circuitry may be of relatively simple design.
8. Frequency response good (however, piezoelectric or capacitance gages are better).

Disadvantages:

1. Under severe conditions calibration does not remain stable.
2. Responds to large vibrations.
3. Low output (higher output may be attained with silicon strain gages, but with some loss of thermal and stability characteristics).
4. Bonded type limited to low range.
5. Installation of bonded or wrapped-type pickups is a critical operation.

6.6 CAPACITANCE

Capacitive pressure transducers^[Cal-Cal6] are widely used in many systems to monitor static or dynamic pressure fluctuations. Two basic types of capacitive transducers are available for pressure applications: the parallel-plate type (most popular) and the concentric overlapping cylinder type as shown in Figures 6.61^[G10] and 6.62. Most often a diaphragm element is used in conjunction with the capacitor (parallel-plate or concentric cylinder type) to provide the displacement necessary for a capacitance change. Devices such as these can operate at high frequencies (approx. 5×10^5 Hz) and are very responsive to rapid pressure fluctuations. Some of the advantages for using capacitive pressure transducers (not considering expense for electronics) are that fabrication can be easy, cost is low, and they are relatively maintenance-free. The more costly items necessary are the electronics; and, depending on the requirements with respect to sensitivity and resolution, this type of pressure monitoring system may be prohibitive for certain applications. The more practical application for such a system would be to incorporate several capacitive transducers into the total system and monitor with one set of electronics.

Capacitance transducers can detect displacements as small as 2.5×10^{-6} cm and produce a measurable electrical signal^[Ca3].

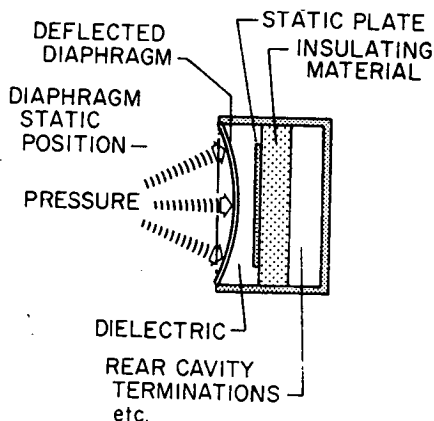


Figure 6.61 Parallel-plate capacitive pressure transducer.

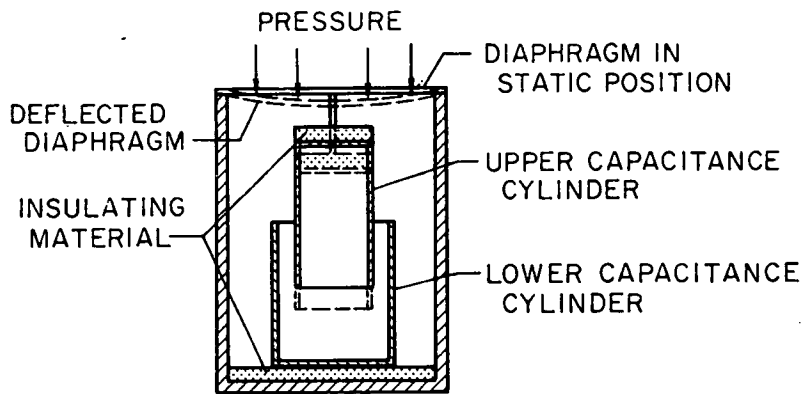


Figure 6.62 Concentric overlapping cylinder capacitive pressure transducer.

A parallel-plate capacitor is limited since the output versus plate separation is a hyperbolic function. However, the non-linearity in this type of device can be minimized by insuring that the displacement is small compared to the plate separation. Also, by inserting a dielectric of appropriate thickness, an almost linear relationship may be reached (see Figure 6.63).

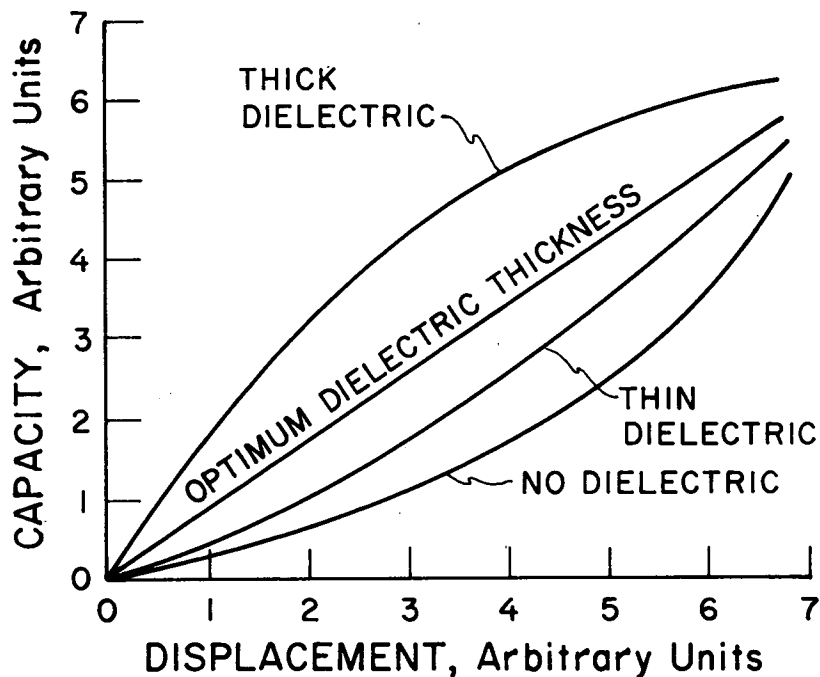


Figure 6.63 Transducer output vs displacement for dielectrics of various thickness.

The addition of a dielectric also increases the sensitivity by a factor equivalent to the change in dielectric constant for the material chosen (for mica the factor is 7).

The equation which describes the electrical capacitance of two parallel plates is given by^[Call]

$$C = 0.0885 \frac{\epsilon A}{L}$$

where

- ϵ = Dielectric constant of the media between the plates
- A = Area of one plate, cm^2
- L = Plate separation, cm.

From the above equation the change in capacitance is related to plate separation by

$$\Delta C = 0.0885 \frac{\epsilon A (-\Delta L)}{L^2}$$

where

- L = Average between initial and final plate separation, cm.

When designing a parallel-plate pressure transducer, several important requirements must be met. First, the plates must be machined flat and as defect-free as possible. The plates must be housed with their faces parallel, and to avoid an extremely non-linear output, they must maintain this parallelism throughout displacement. Another factor requires that the material and geometry choice maintain the initial plate separation during temperature changes should any occur. Some capacitive pressure transducers are extremely sensitive to temperature variation^[Ca5].

Many capacitive pressure transducers can withstand 300 percent overloads and temperatures to 400°C with approximately one percent or less change in calibration.

If a diaphragm is used, as with most capacitive transducers, it must not have a natural frequency or an appreciable harmonic in the range of pressure oscillations likely to be encountered (see "Diaphragms" for the natural frequency equation).

A second type of capacitive pressure transducer uses two concentric, overlapping, cylinders. This device is basically the same as the parallel-plate type with one important exception: the output of the transducer is a linear function of its displacement.

For concentric, overlapping cylinders the equation which describes the electrical capacitance (C) is given by^[Call]

$$C = \frac{0.242 \epsilon L}{\log_{10} \left(\frac{D}{d} \right)}$$

where

- ϵ = Dielectric constant of the media between the cylinders
- L = Length of cylinder overlap, cm
- D = Inner diameter of the outer cylinder
- d = Outer diameter of the inner cylinder.

If the cylinder overlap is not large, end effects will not produce a non-linearity. The change in capacitance (ΔC) of concentric cylinders is related to displacement (ΔL) by

$$\Delta C = \frac{0.242 \epsilon \Delta L}{\log_{10} \left(\frac{D}{d} \right)}$$

The advantage of this system is that a proportional relationship exists between capacitance and displacement, and the calibration is independent of L . This allows for easier calibration since the exact reproduction of L is not necessary each time.

Calibration techniques for both types of capacitance pressure transducers are essentially the same^[Cal]. A calibrated variable air condenser is placed in parallel with the measuring capacitor, and a pressure is applied to the system. While held at pressure, the variable condenser is adjusted to "null" the output, and the capacitance reading is noted. This "null" calibration technique is good because it is independent of the circuit characteristics. A simplified block-diagram of the circuitry necessary for parallel-plate or concentric cylinder type transducers is shown in Figure 6.64.

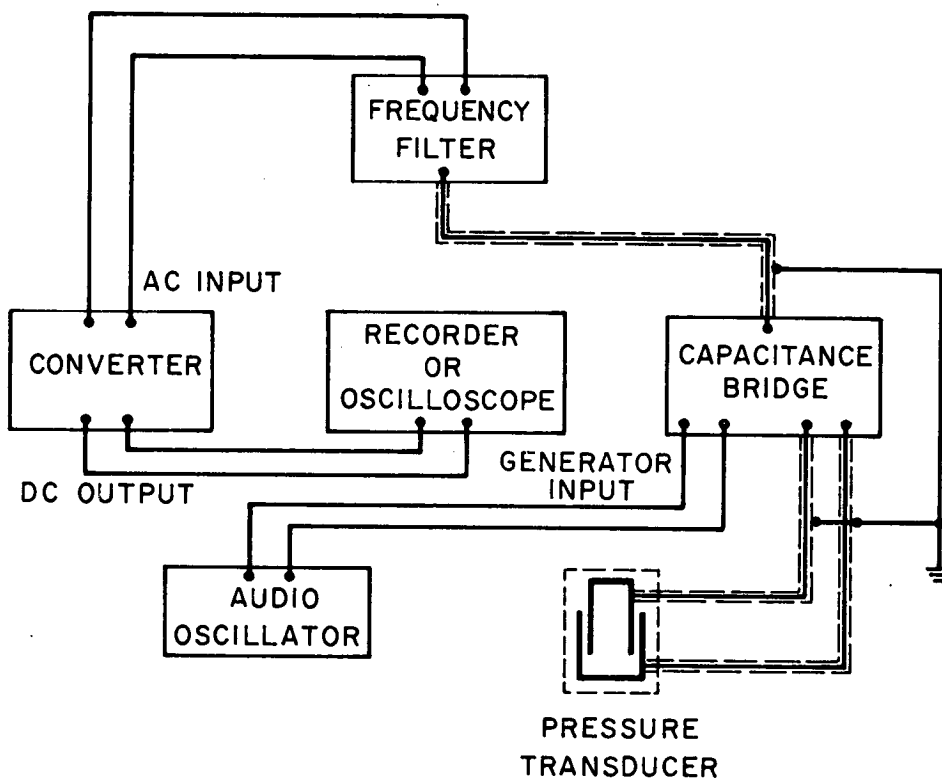


Figure 6.64 Electrical circuitry for capacitance pressure transducers.

All other design considerations outlined for the parallel-plate capacitor are also applicable for a concentric cylinder device.

During operation with either type of capacitance transducer it is imperative that misalignment (plate or cylinder cocking) does not occur since when this happens all linearity is destroyed.

Advantages:

1. Lightness and stiffness of the moving parts give rise to a short natural period and, therefore, very responsive to high frequencies.
2. The elastic member can be chosen for consistency and freedom from hysteresis.
3. Sensitivity can be varied over a wide range.
4. Ease of fabrication.
5. Pickup can be made small (particularly the parallel-plate type).
6. Transducer may be mounted directly adjacent to stream.
7. Linear output (for concentric, overlapping cylinder design).
8. Ability to measure a static quantity (i.e., when pressure is increased and held constant, the capacitor will produce a steady signal).
9. Adaptable to widely different forms of construction.
10. Relatively insensitive to shock and vibration.
11. Mechanical linkage not always required between pressure diaphragm and electrically sensitive element.
12. High frequency response.
13. High-temperature resistance (not to imply temperature insensitive).
14. Excellent resolution.

Disadvantages:

1. Temperature sensitive (excessive drift for nonequilibrium temperature conditions).
2. Comparative complexity of associated electronic equipment.
3. Relationship between displacement and output is hyperbolic (for parallel-plate transducers).
4. High overall cost.
5. Shielded cable must be used.

6.7 PIEZOELECTRIC

When certain crystals are elastically deformed along specific planes of stress, an electrical potential is produced in the crystal. This phenomenon is known as the piezoelectric effect, and several crystals exhibit this behavior. A piezoelectric pressure transducer incorporates a crystal in such a way that as the pressure is applied, an electrical output is produced which is proportional to the applied stress (see Figure 6.71).

Piezoelectric crystals may be used without additional excitation; however, the output signal is very small and necessitates amplification. Most often piezoelectric crystals are used in conjunction with external excitation and are sometimes stacked in parallel for increased output (see Figure 6.74).

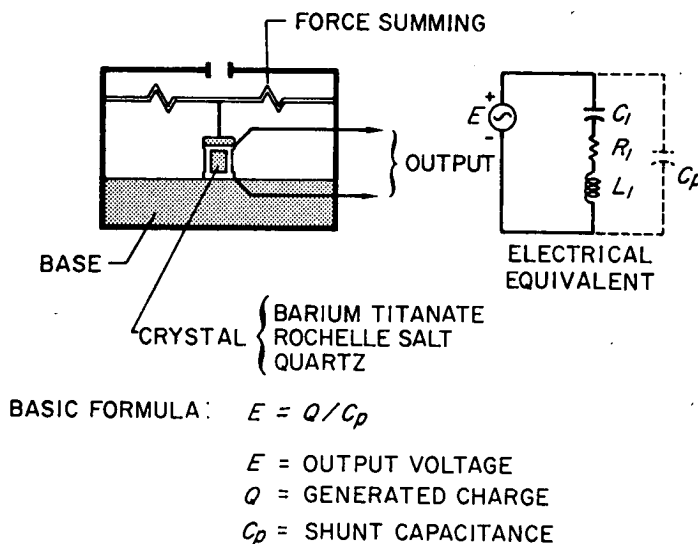


Figure 6.71 Schematic of piezoelectric pressure transducer and related circuitry.

Measurement of pressure can be accomplished by using a piezoelectric crystal operating at a fixed frequency which varies with the media being measured.

Output is dependent on the Q factor for a given crystal and is defined as the ratio of average stored energy in the crystal to the energy dissipated per cycle^[P1]. This factor varies with the type of crystal chosen and loading conditions. It is therefore necessary to employ a crystal that has a minimum loss due to internal friction to achieve high sensitivity.

It can be shown that changes in the crystal Q produced by loading are inversely proportional to pressure for crystals vibrating in extension and flexure, and inversely proportional to the square root of pressure for shear mode elements^[P1]. Experiments have shown quartz to be a suitable high-frequency crystal vibrating in the thickness shear mode. Crystals such as these, when properly etched, polished, and mounted (by pressure clamping) can exhibit Q factors of 500,000 or more in vacuum.

Not all crystals, however, are piezoelectric. There are two main groups of piezoelectric crystals: (1) those such as quartz which occur naturally and (2) synthetically produced crystals (such as Rochelle salts). Some of the more commonly used crystals include quartz, tourmaline, ammonium dihydrogen phosphate (ADP), barium titanate, Rochelle salts, sucrose, and tartaric acid^[G1,P3]. The advantages vary from crystal to crystal, and one is chosen on the basis of a particular application. Tourmaline is the least active chemically, while tartaric acid is the most active electrically. The crystals which occur in nature, such as quartz, have the advantage of very low electrical leakage which, when used with an electrometer or very high impedance input, permits the measurement of slowly fluctuating pressures. They are, therefore, capable of withstanding higher temperatures, operating at low frequencies, and sustaining shock. Synthetic crystals exhibit a much higher output for an applied stress. However, they are usually unable to withstand high mechanical strain without fracture. Also, the synthetic crystals have an accelerated rate of deterioration over the natural ones.

The piezoelectric device is generally used as a dynamic pressure sensor due to the device's high electric impedance at low frequencies. Figure 6.72 for illustration purposes, is an exaggerated example of how piezoelectric crystals respond to a step pressure^[G1].

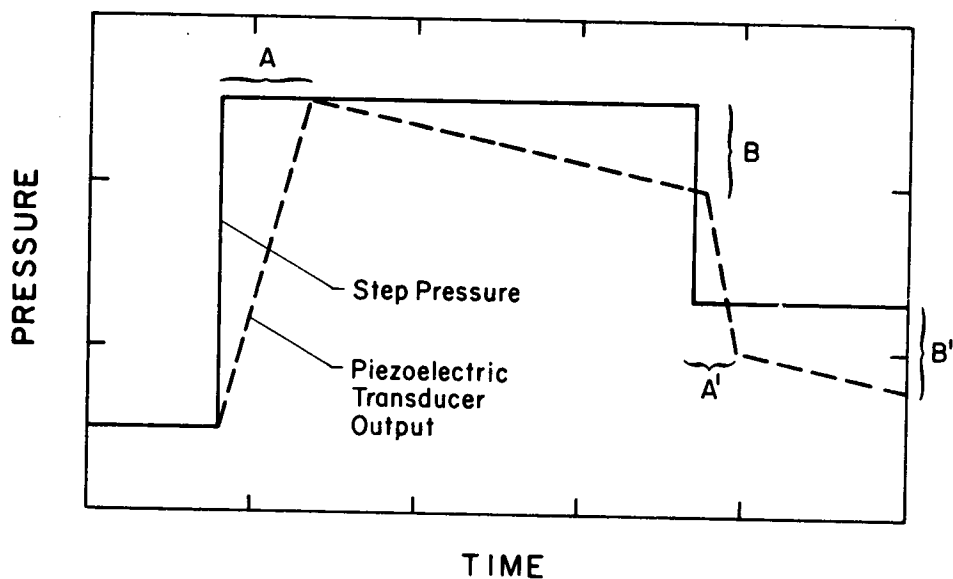


Figure 6.72 The response characteristics of a piezoelectric pressure transducer.

The horizontal differences depicted by A and A' are primarily due to the finite response of the transducer, and vertical discrepancies B and B' are caused by electrical leakage in the crystal.

The major advantage of a piezoelectric pressure transducer is that the signal response to a pressure variation is linear, and frequency responses up to 10^6 Hz or more are obtainable. Reproducibility of results is obtained by careful control of operating temperature. The transducer is light in weight, compact and rugged.

A comparison of sensitivities for three crystals is shown in Figure 6.73^[P3].

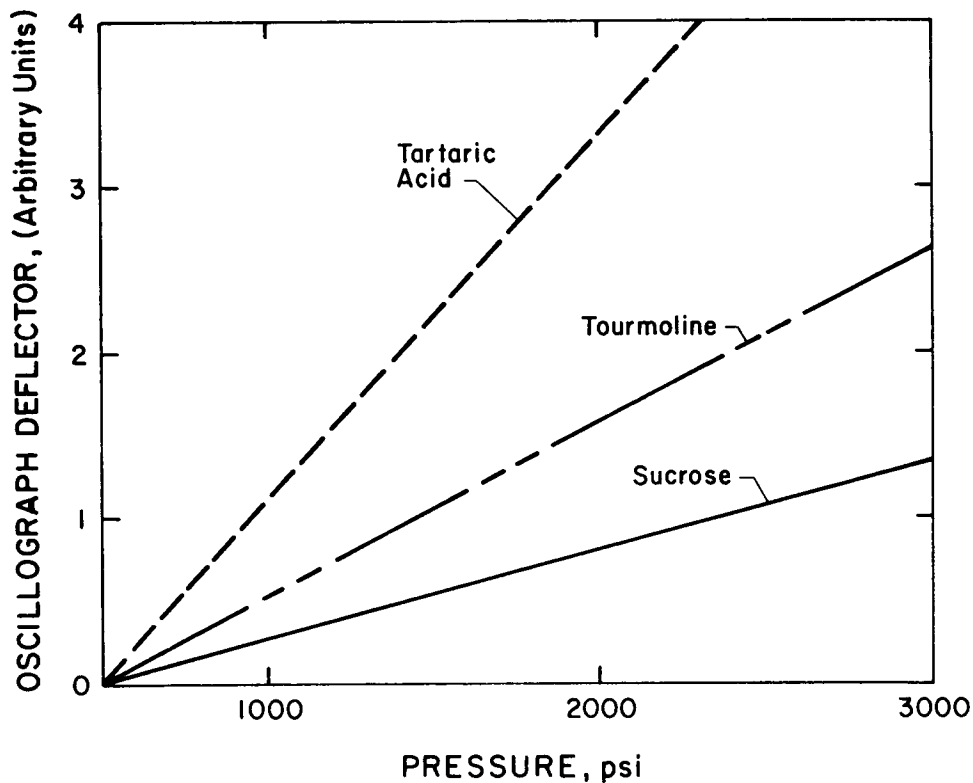


Figure 6.73 Piezoelectric crystal sensitivity.

Quite often in the design of piezoelectric transducers, quartz or other natural crystals are chosen over the high-output synthetic ones, and the output is increased by "stacking". Stacking, as shown in Figure 6.74, is an effective way to increase high-frequency response and sensitivity. The output of this type of transducer is significantly greater than that of a single element, but the signal generated is still low, and consideration must be given to electric and magnetic shielding and short cable lengths.

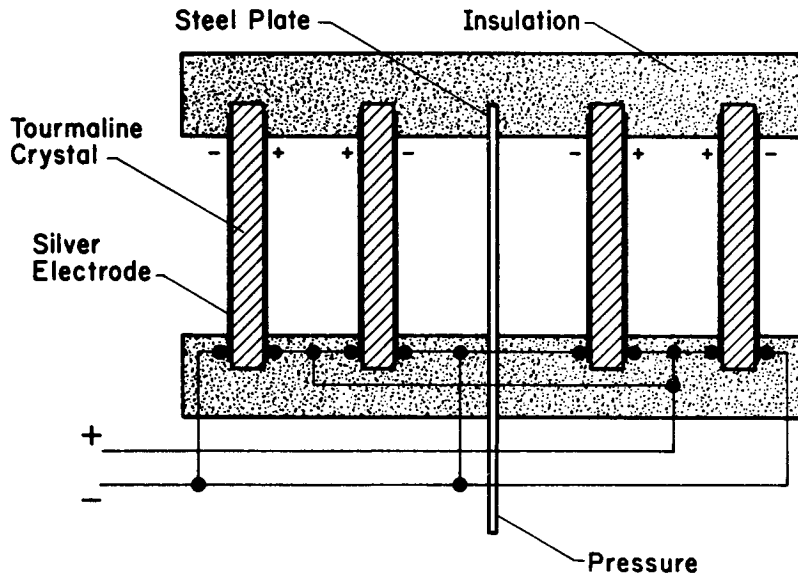


Figure 6.74 Piezoelectric crystals stacked in parallel.

Piezoelectric crystals are very sensitive to vibration (or frequency changes) and temperature changes. Therefore, it is imperative that stability in all circuit components be maintained which will affect the oscillatory frequency of the sensing crystal. Temperature differences will produce the most serious frequency change, affecting both the crystal (since it necessarily has a temperature coefficient of frequency) and related circuit components. If the temperature coefficient is known for the crystal and a stability of one part per million can be maintained in the oscillator circuit, the pressure may be determined to an accuracy of 0.7 millibars with a crystal that changes frequency 1,400 parts per million per atmosphere.

The block diagram in Figure 6.75 illustrates a typical complex circuitry necessary for piezoelectric pressure transducers.

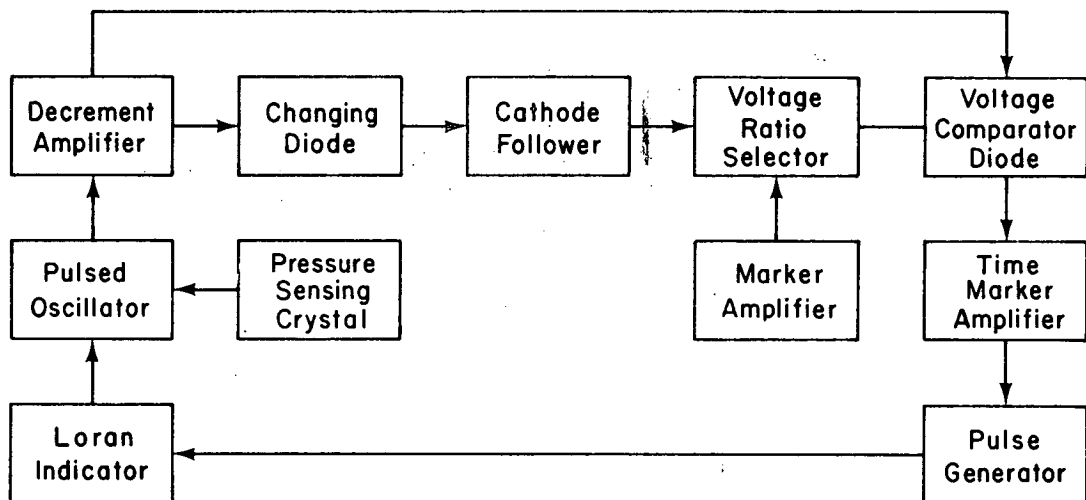


Figure 6.75 Block diagram for piezoelectric pressure transducers.

PIEZOELECTRIC SPECIFICATIONS

Types of pressure measurement (including base limitation for differential):

Ballistic pressure transient, air blasts, underwater blasts, rocket blasts, shock tube measurements, internal-combustion engines, and many others.

Pressure ranges:

Dependent on elastic limit of crystal chosen; typically, piezoelectric crystals range from 10^{-6} psi to 10,000 psi. Frequency response: up to 1.0×10^6 Hz.

Accuracy:

Assuming the temperature coefficient of the crystal is known and a stability of one part per million can be maintained in the oscillator circuit, it should be possible to determine pressure to an accuracy of 0.7 millibars with a crystal that changes frequency 1,400 parts per million per atmosphere.

Temperature (range, compensation, and stability):

Temperature stability is good when device has been compensated.

Calibration:

No static calibration possible. Dynamic calibration tricky.

Vibration effects:

Appreciable (unless compensated): also highly sensitive to electrical noise.

Materials:

Crystal materials include: quartz, tourmaline, ammonium dihydrogen phosphate (ADP), barium titanate, Rochelle salts, sucrose, tartaric acid, and others.

Oxygen usage:

When pressure transients are to be measured, piezoelectric pressure transducers are probably the choice of any type for use with gaseous or liquid O_2 . When used with cold gaseous or liquid O_2 proper crystal selection is important, since synthetic types are usually unable to withstand high mechanical strain without fracture.

Installation requirements and limitations:

Crystal mounting becomes critical where vibration in the holder may affect the oscillating frequency.

Remarks:

Unique in ultra-high frequency range. Poor in very low frequency range.

Advantages:

1. Highly linear response.
2. Calibration remains constant.
3. High frequency response.
4. High output (1.0 to 30 mV/g).
5. Negligible phase shift.
6. Small size.
7. Rugged construction.

Disadvantages:

1. Piezoelectric crystals used in parallel (as shown in Figure 6.74) require an extremely high-gain amplifier.
2. Responds to severe vibration.
3. Extreme care must be taken to minimize leakage in the input circuit of the high-gain amplifier.
4. Unsuitable for static pressure measurements.
5. Unsuitable for measurements of extremely low pressures.
6. Very sensitive to temperature changes.
7. Very sensitive to cross-accelerations..
8. Long cables generate spurious response or noise.
9. After extreme shock does not return readily to original calibrated zero.

6.8 POTENTIOMETRIC

Potentiometric pressure transducers employ electro-mechanical devices which use a force-summing element (e.g., Bourdon tube, bellows, or diaphragm) to drive a variable resistor. In the low pressure ranges a capsule, multi-capsule, or bellows may be used, and for high pressures (to approximately 100,000 psi) a Bourdon tube is necessary. In all cases the electro-mechanical element is a variable resistor in which the motion of the movable contact or slider is powered by a diaphragm capsule, bellows, or Bourdon tube. The output voltage from the variable resistor is altered by displacement of the force-summing element due to a mechanical coupling between the resistor and force-summing element. A properly designed potentiometric pressure transducer will incorporate a diaphragm, bellows, or Bourdon tube having deflectional properties which are proportional to the applied pressure (see appropriate section Bellows, Diaphragm, etc.).

Schematic diagrams are shown in Figures 6.81-6.83 for both low and high pressure range transducers with each having comparable circuit diagrams.

Resistor elements for a potentiometric pressure transducer can be of the finite or continuous resolution type. The former is a wire-wound element with the output voltage changing in discrete steps proportional to the wire and core diameter, while the continuous resolution device is fabricated from conductive plastic with the output voltage changing in a continually smooth fashion.

For the circuitry necessary to operate a potentiometer (shown in Figure 6.82), it is imperative that the applied potential be maintained constant for stability. A single pointer-type instrument is used, and a two-position switch is connected in order to make it possible at any time to check the applied potential. By operating the checking switch, the potential across the entire length of the slidewire may be measured and adjusted by means of the variable resistance R. The applied potential is

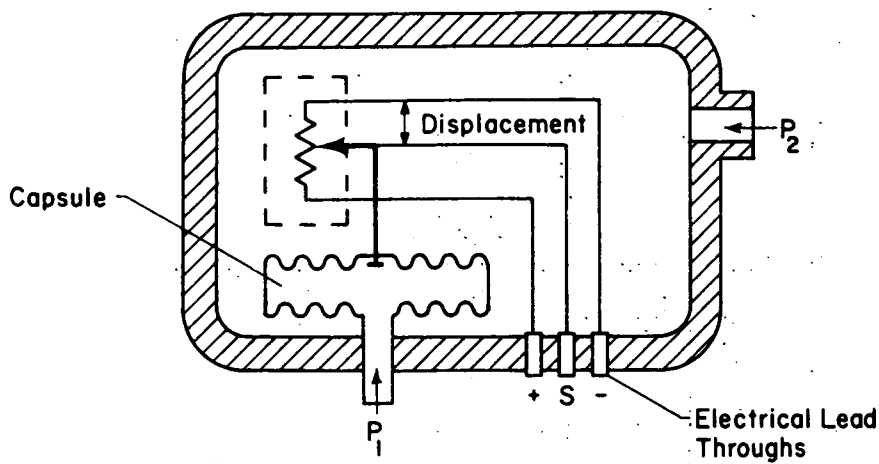


Figure 6.81 Potentiometric pressure transducer using a capsule element.

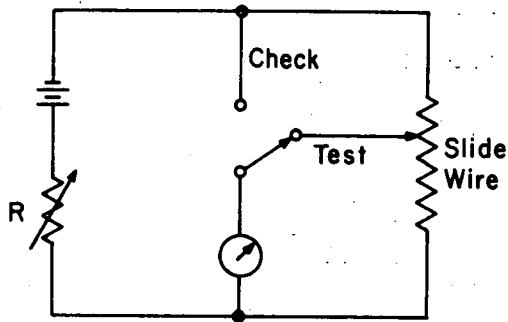


Figure 6.82 Circuitry for potentiometric devices.

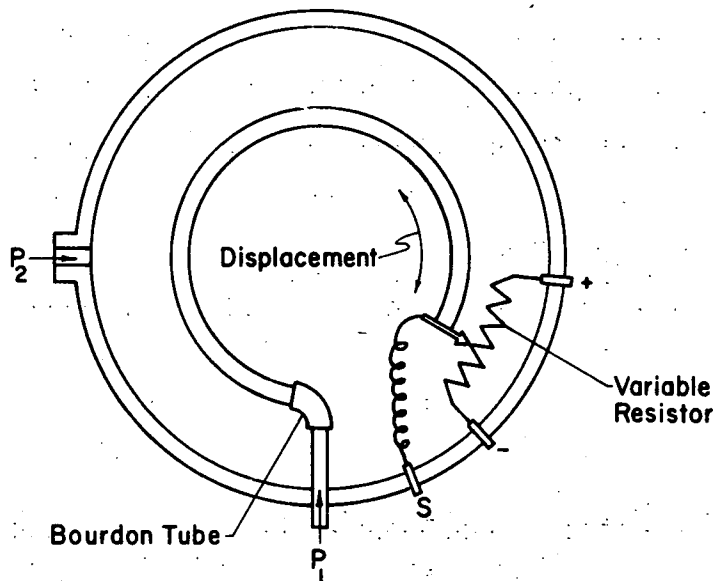


Figure 6.83 Potentiometric pressure transducer using a bourdon tube element.

adjusted until the indicating instrument shows a full-scale deflection; then, with the switch in the test position, the deflection of the instrument indicates the position of the sliding contact. The above circuit requires a calibration to correlate contact movement and position with applied pressure^[G1].

Recently, the "error band" concept (DEB -- dynamic error band, SEB -- static error band, etc.) has been used by designers for specifying or describing pressure transducer performance. A static error band (SEB), for example, would include prime errors of linearity, hysteresis, resolution, repeatability and fraction with respect to how much each contributes to the total error (for a complete discussion of this concept see Reference Po2). The graph in Figure 6.84 shows relatively how much error is introduced for a given pressure range.

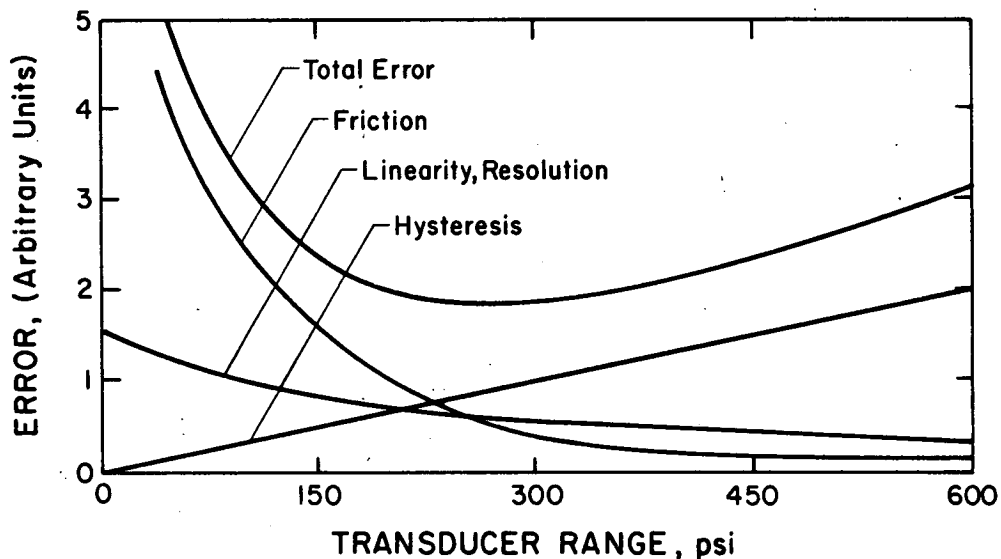


Figure 6.84 Error contribution in a pressure transducer.

It is obvious that the major contributing error at very low pressure ranges is friction and at very high ranges, hysteresis^[Po5]. Therefore, for low pressure ranges it is advantageous to provide larger effective cross-sectional area sensors and with high pressure sensors less deflection must be considered (force-summing element displacement must be multiplied to restore desired wiper displacement). Intermediate pressure ranges involve the optimization of all parameters to minimize total transducer error^[Po3].

Potentiometric transducers are often called upon to measure corrosive or electrically conductive media. This presents no problem when the fluid enters the device at P_1 (see Figure 6.85). However, if such a liquid or fluid (oxygen is possible) is also introduced at P_2 , a modification of the transducer is necessary to insure against unwanted reactions. The figure illustrates one possible solution which isolates all electrical components from the fluid being measured by installing a slack diaphragm as shown.

The electro-mechanical compartment is then filled with a neutral fluid, thereby isolating those elements from the measuring stream.

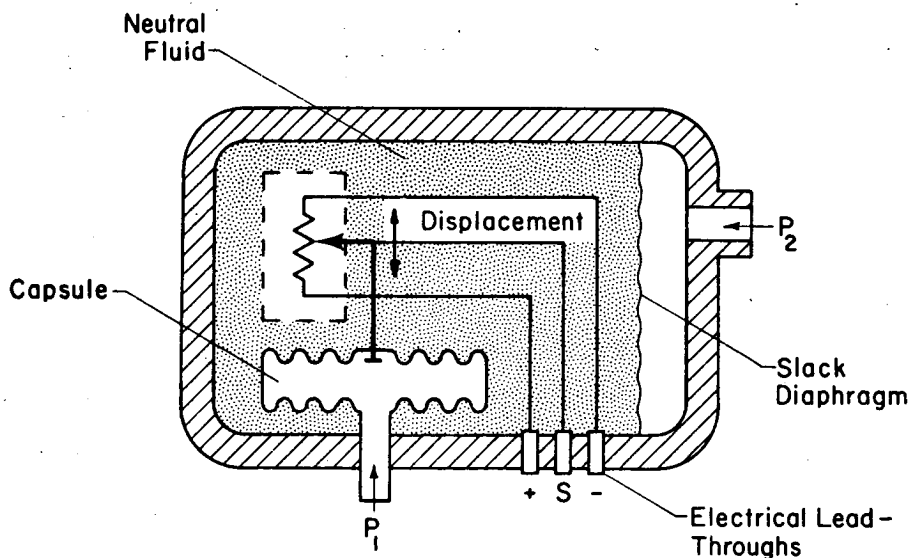


Figure 6.85 Pressure transducer component isolation for use with reactive liquids or gases.

POTENTIOMETRIC SPECIFICATIONS

Types of pressure measurement (including base limitation for differential):

Gage, vacuum, differential, and absolute. Base pressure is limited by the type of force-summing element chosen (Bourdon tube, bellows, etc.).

Pressure ranges:

Dependent on force-summing element chosen (see proper section for description).

Resolution:

0.2 percent of full scale.

Accuracy:

± 0.25 percent terminal end-point accuracy.

Temperature (range, compensation, and stability):

High and low (cryogenic) temperature transducers available.

Some devices are temperature-compensated by mechanical methods (see "Force-Summing Devices") and others use electrical compensation.

Stability is good if input potential is maintained constant.

Calibration:

Transducer output and input is measured at incremental values of increasing and decreasing pressure from 0-100 percent of full range.

Vibration effects;

Very insensitive.

Materials:

Electrical wiring, resistors, and force-summing device (see section on Bourdon tube, bellows, or diaphragm).

Oxygen usage:

Yes, with properly designed transducer (see paragraph describing the "isolated" transducer). Corrosion resistant, explosion-proof, and cryogenic potentiometric pressure transducers are currently available.

Installation requirements and limitations:

Generally, the transducers are large; however, miniaturization has been accomplished with some sacrifice in performance. Also, for less demanding installations (where space is not a problem) servo-power is used to reduce friction.

Advantages:

1. Inexpensive
2. High output
3. AC or DC excitation
4. No amplification or impedance matching (sometimes)
5. Very wide range of function (characteristic)
6. Can be ruggedly constructed
7. Vibration and temperature insensitive

Disadvantages:

1. Resolution is finite (wirewound type).
2. High mechanical friction (a very important factor for low pressure transducers).
3. Limited life (wire wear).
4. Transducer becomes noisy with wear
5. Large displacements required
6. Generally low frequency response

MAGNETIC PRESSURE TRANSDUCERS

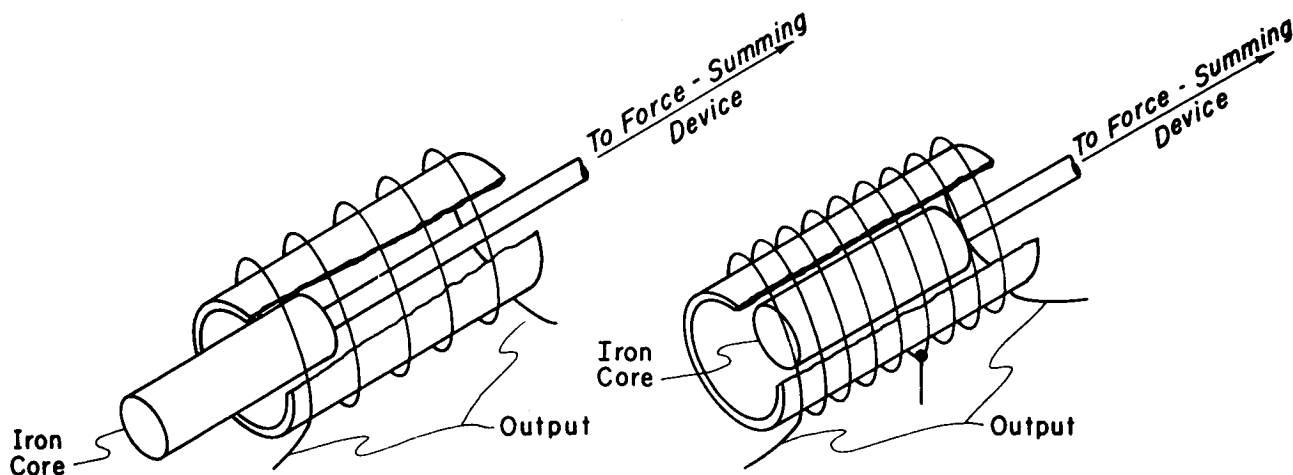
Magnetic pressure transducers comprise two groups: (1) those which operate through a change in inductance and (2) those which utilize the change in reluctance of a part of a magnetic circuit. There is no clear line of distinction between the different types.

The magnetic type pressure transducers must always be supplied with energy, the variable-inductance types being activated by electromotive forces and the variable-reluctance units by magnetomotive forces. The circuitry for either the inductance or reluctance pressure-measuring devices is usually of low impedance and capable of carrying relatively large currents, many of which need no amplification.

Magnetic pressure transducers are coupled with either a Bourdon tube, bellows, diaphragm, or U-tube. The displacement of the element is converted to an electrical signal (output) which is proportional to the applied pressure. The following two sections describe the basic operation of variable-inductance and variable-reluctance pressure transducers.

6.9 INDUCTANCE

One of the simplest forms of magnetic transducers is the variable-inductance unit. It consists of a coil of many turns of wire wound on a tube of insulating material with a movable core of magnetic material (see Figure 6.91).



VARIABLE - INDUCTANCE

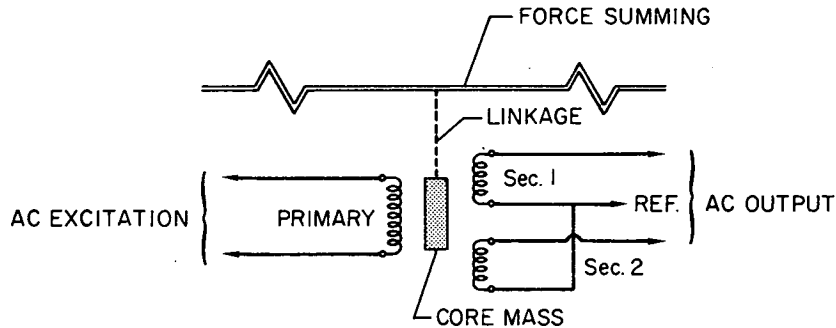
INDUCTANCE - RATIO

Figure 6.91 Inductance technique commonly used in pressure transducers.

As the coil is energized and the core enters the solenoid cell, the inductance of the coil increases in proportion to the amount of metal within the coil.

The inductance-ratio element is also shown in Figure 6.91 and its principle of operation is similar to the variable-inductance unit. In this case, however, the windings are center-tapped creating two inductors and upon displacement of the core an increased inductance in one coil takes place while inductance of the second coil decreases. This arrangement provides for increased sensitivity and linearity of response over that of the variable-inductance unit and can also be used to detect positive and/or negative displacements. Compensation for temperature, lead resistance, and other factors can be easily incorporated into the system.

The mutual-inductance unit for displacement measurements is shown in Figure 6.92 and is sometimes called a linear, variable, differential, transformer (LVDT).



$$\text{BASIC FORMULA: } C = (N \frac{d\phi}{dt}) \text{ Sec. 1} - (N \frac{d\phi}{dt}) \text{ Sec. 2}$$

C = OUTPUT VOLTAGE

N = NUMBER OF TURNS

$d\phi/dt$ = RATE OF CHANGE IN WEBERS

Figure 6.92 Inductance-ratio circuitry.

In this device the effective impedance of a coil is altered by changing the mutual inductance between it and another circuit. As shown, the device has one primary and two secondary windings with the core mass centered on the primary winding. When ac current is supplied to the primary winding (with the armature centered), the magnetic flux generated by this coil is distributed by the armature so that equal voltage is induced in each of the secondary coils. Then, upon displacement of the armature, either positive or negative, the resultant will be a voltage rise in one secondary and a decrease in the other. Figure 6.93 illustrates this principle for a typical LVDT.

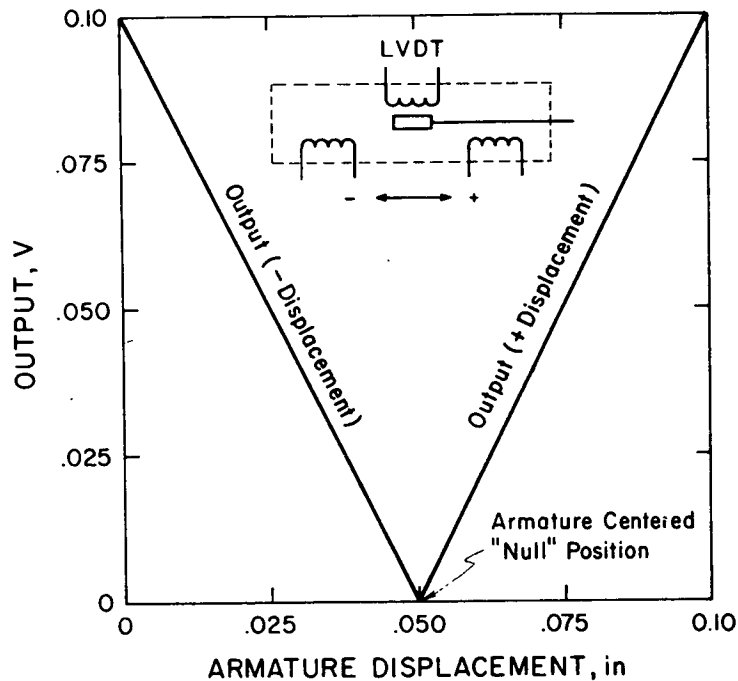


Figure 6.93 Output vs armature displacement for LVDT pressure transducers.

The electronic circuits used in combination with variable-inductance transducers can be one of three types: (1) simple series circuits, (2) series-opposition circuits, or (3) bridge-type circuits and any one of these may also include amplification. A commonly used circuit for variable-inductance systems is shown in Figure 6.94.

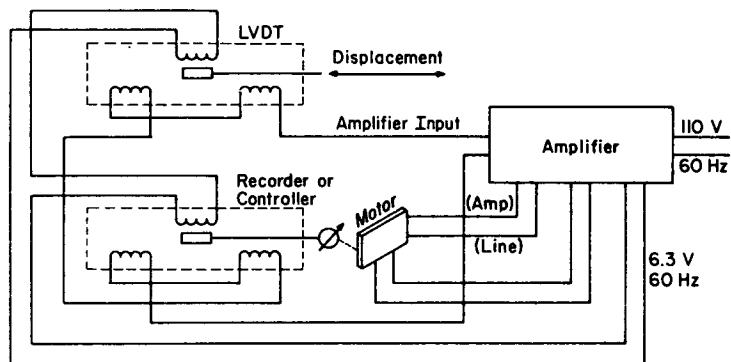


Figure 6.94 Inductance pressure transducer circuitry.

Advantages:

1. Responsive to static or dynamic conditions.
2. Construction can be extremely simple.
3. Continuous resolution.
4. Low hysteresis.
5. Signal-to-noise ratio is high.
6. High output.
7. No frictional load on system.
8. Exerts little or no reaction forces on the measuring device.
9. Results in linear electrical response when actuated by linear mechanical motion.
10. Operates from 60 Hz current and does not require special power supplies.
11. Voltage required is only 3 volts per unit for most applications.
12. Small, rugged, and dependable.
13. Can operate underwater.

Disadvantages:

1. Not particularly sensitive.
2. Requires shielded cable.
3. Must be excited with ac only.
4. Sensitive to vibration.
5. Frequency response is limited to the force summing device (diaphragm, bellows, etc.) used.
6. The units are large and have a low frequency response.
7. Instrumentation must be selected to operate on ac signals, or rectifier must be used for dc output.

6.10 RELUCTANCE

The reluctance type pressure transducer thus consists of a device for converting pressure into the proper type of displacement, i.e., a diaphragm for the single-active-arm bridge circuit or a torsion tube for the others, a suitable magnetic core to complete the magnetic circuit, and the required number of inductive coils. Additional electronics (for the electromagnetic type) include a carrier oscillator supply, a demodulator, and a recording device. The latter is usually a galvanometer type oscillograph, although the transducer can be used quite readily to drive an oscilloscope or magnetic tape recorder.

Variable-reluctance pressure transducers are distinguished primarily by how the exciting energy enters the system. The energy is introduced as a magnetomotive force which may be produced by an electromagnet assembly or permanent magnet.

Electromagnetic induction is the means by which the variable-reluctance system operates. This can be accomplished by two or more methods. First, a magnetic field is created, either electrically or with a permanent magnet, and a moveable iron core is placed near this field. Then, as the iron core is displaced, a resultant change in flux occurs which can be proportional to the rate of pressure change. The second method also uses a magnetic field with a conductor in it; however, it remains stationary and the field strength changes producing current flow. In either case it is the interaction of a magnetic field and an electric conductor which produces a current; a change of armature position or flux is always involved. The following schematic in Figure 6.101 is a simplified illustration of the variable-reluctance principle^[G1].

This type of pressure transducer does not measure pressure, but instead the rate of change of pressure and hence presents a number of difficulties. The major problem is not being able to perform a static calibration or measurement with this system. This problem also exists for piezoelectric

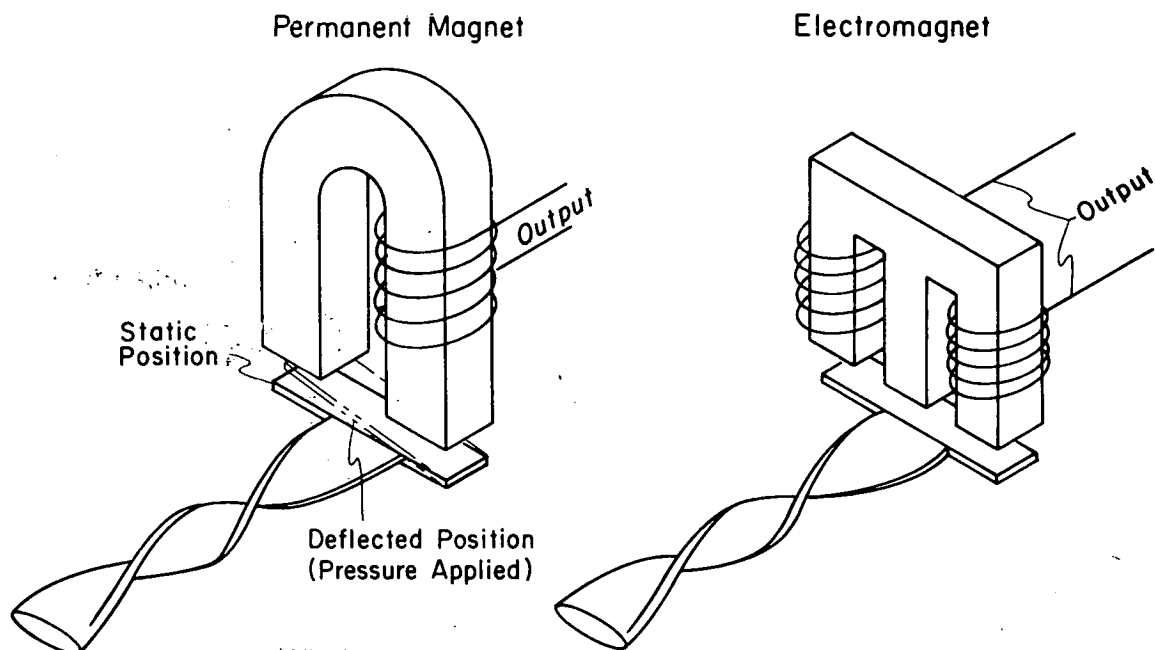


Figure 6.101 Basic principle of reluctance technique.

transducers, but the reluctance type does not possess the redeeming features of extremely high frequency response which is characteristic of the crystal. Hence, it is limited to a small number of specialized uses.

Figure 6.102 shows three arrangements for variable-reluctance bridge transducers. The first utilizes a flat diaphragm in conjunction with three fixed inductance arms and one active. Next, a rotating armature is used (actuated by a torque-tube) with two active and two fixed inductances. In this case sensitivity and frequency-response is enhanced over the first example. The last variable-reluctance pressure transducer maximizes sensitivity and frequency-response by incorporating four active inductance arms into the circuit.

The output of the two- or four-active arm bridge transducers is sufficiently high that amplification is generally not necessary. Frequency response of the transducer is limited either by the mechanical characteristics of the armature or the carrier frequency, which in turn depends on the power absorbed and heat generated by the magnetic circuit. A typical carrier

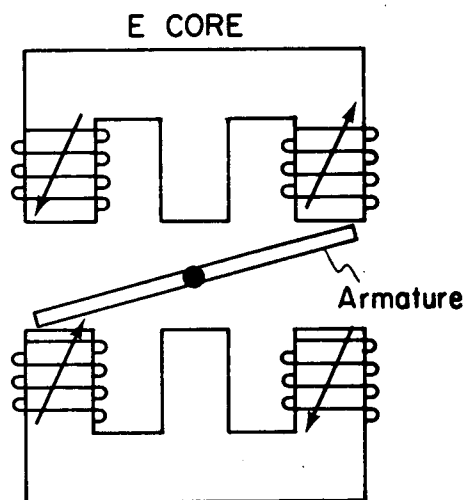
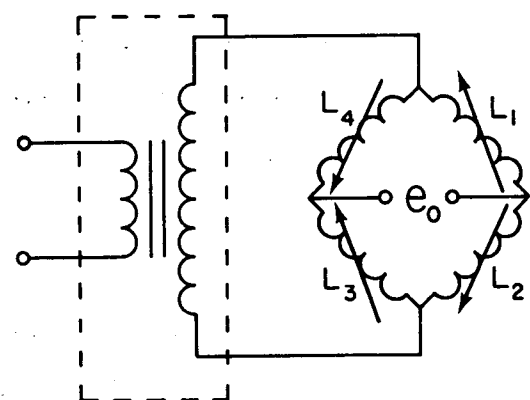
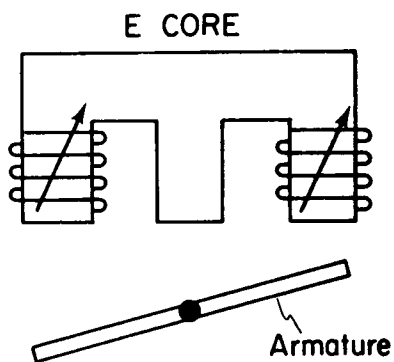
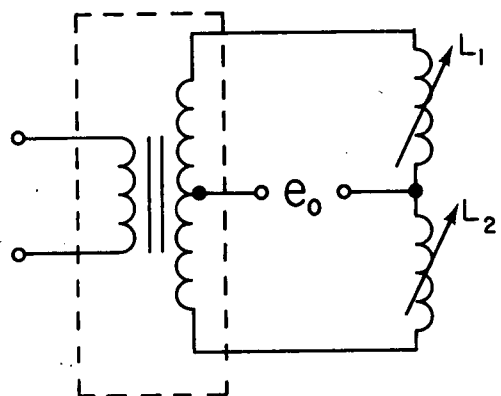
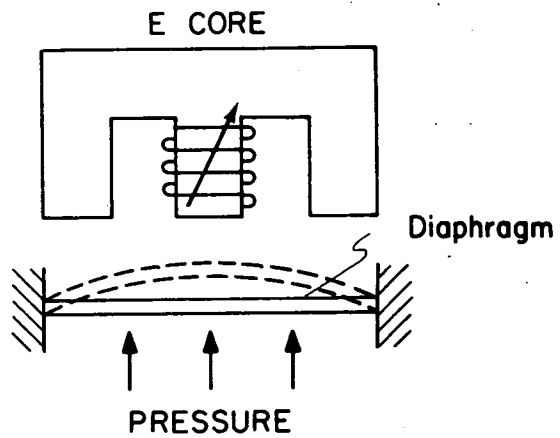
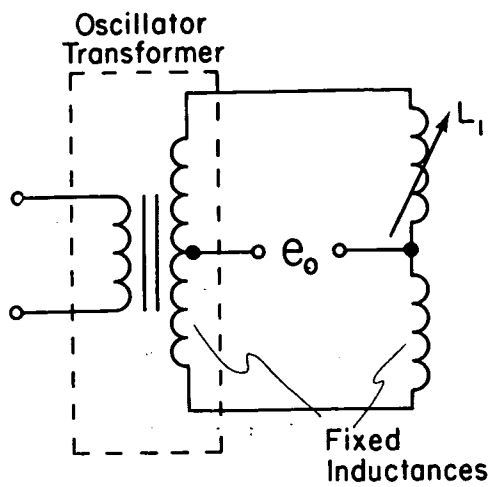


Figure 6.102 Circuitry for reluctance pressure transducers.

frequency for the rotating-armature type pickup is 3×10^3 Hz, which limits the frequency response of these types to the order of 1×10^3 Hz^[G16]. The following block diagram shown in Figure 6.103 is typical of a variable-reluctance pressure transducer measuring system.

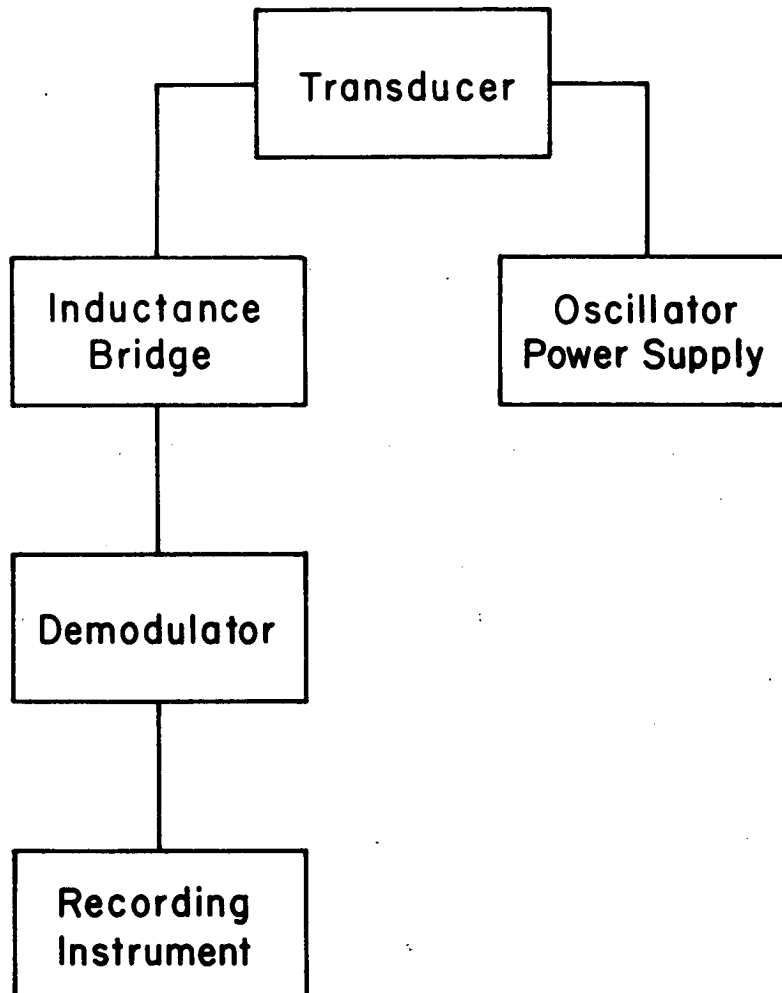


Figure 6.103 Block diagram of variable-reluctance pressure transducer circuit.

Advantages:

1. Responsive to static or dynamic conditions.
2. Continuous resolution.
3. High output (≥ 40 mV/V). The high output (up to 10 ma for a 50-ohm load) is sufficient to actuate a high-frequency galvanometer or may be used to operate a recording galvanometer, a millivolt recorder or indicator, or a milliammeter.
4. Signal-to-noise ratio is high.
5. One type gives rate of pressure change directly.
6. No mechanical linkages necessary between diaphragm and electrically sensitive element.
7. This type of pressure transducer may be used with telemetering systems of the frequency-modulated or pulse modulated types and with servo systems.

Disadvantages:

1. System does not function well in close proximity to magnetic objects, or fields.
2. Large size and low-frequency response.
3. Reactive and resistive balancing required.
4. Must be excited by ac only.
5. Frequency response limited to force-summing device chosen (diaphragm, bellows, etc.).
6. For some types a complicated high-gain amplifier is required to integrate accurately the rate of pressure-change response into pressure-time response over the required frequency range.
7. Other types which require ac impedance electrical circuits do not give accurate reproduction of high-frequency components unless a very high-frequency current is used.
8. Static calibration not possible.
9. Cannot measure low-frequency variations.

OTHER PRESSURE TRANSDUCER TYPES

The following section introduces in limited detail some other pressure transducers. These units are found in specialized applications, or their operational principle may be used in a custom fabrication. A brief description of the unit, its method of operation, a schematic drawing and related circuitry will be given for each type of transducer, followed by references and bibliography.

6.11 MICROMANOMETERS

Micromanometers are defined as "...instrumentation used to measure pressure, either absolute or differential, in the range from about 0.001 to 50 mm of Hg (0.13 to 6650 Nm^{-2})" [Mi5]. Some of the types of devices classified as micromanometers include U-tube; diaphragm-capacitance; elastic element (optical); inductance; resistance wire; gas column; vacuum tube; piston gages; and centrifugal transducers.

Since micromanometers are similar in operational principle to those described in this report, the discussion here will be limited to types and general description. NBS Monograph 114 is given as an excellent reference (Mi5) on micromanometers. It furnishes detailed information on types, methods of measurement, pressure oscillations, and calibration techniques.

As with other transducers, the unit of pressure commonly used for micromanometers is either millimeter of mercury (mmHg), millimeter of water (mmH_2O), or inches of water (in. H_2O). The unit quite often used for vacuum or low pressure measurements is the torr (see Preface).

Brombacher [Mi5] indicates "A gas pressure in the micromanometer range may be measured in four fundamental ways. These are: (a) by means of a balancing liquid or gas column; (b) by the strain produced in an elastic element; (c) by a balancing gravitational force; and (d) by a balancing centrifugal force. Other methods of measuring pressure in the micromanometer range, such as thermal conductivity, viscosity, radiation, and ionization, are more applicable to the higher vacuum ranges."

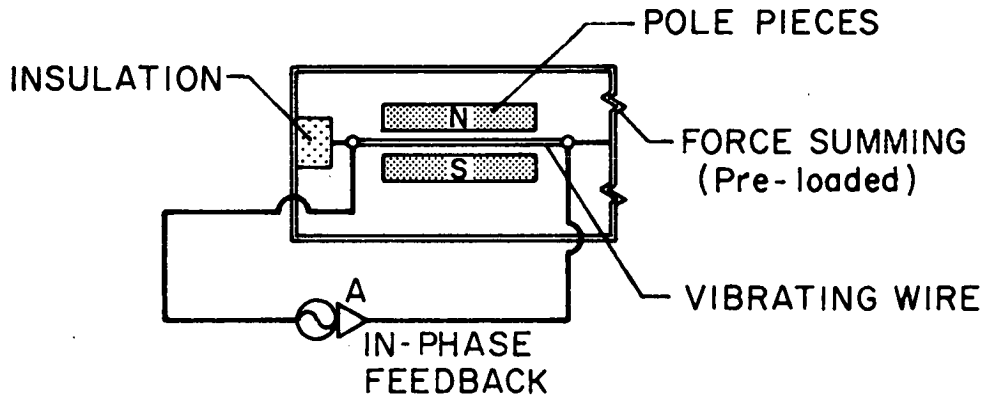
Generally all pressure transducers in the micromanometer range which use the four primary methods for sensing pressure involve the amplification or conversion of the primary signal.

Often in a system, particularly containing reactive gases, the pressure gradually decreases on standing. A great advantage of the micromanometer is that continuous monitoring of the pressure in a reservoir is possible and any changes can be immediately detected.

According to Brombacher, "the principal laboratory applications for micromanometers have been in investigating gas reactions, in making chemical analyses, in measuring low vapor pressures, atmospheric pressure fluctuations, low gas velocity by impact pressures, and low differential pressures at high pressures. Their principal industrial application appears to be in petroleum refining."

6.12 VIBRATING WIRE

The vibrating wire (or ribbon generally of tungsten) is usually very fine, stretched in a magnetic field, and set into oscillation. Figure 6.121 illustrates the device and circuitry necessary.



BASIC EQUATION: $F = K\sqrt{TeL}^2$

F = FREQUENCY

T = TENSION

e = LINEAL DENSITY

L = LENGTH

Figure 6.121 Vibrating wire pressure transducer.

The wire is pre-loaded and an electrical signal is generated and amplified. Part of the amplified signal is fed back, in phase, to the oscillating wire and the mode of vibration is maintained. Vibrational frequency of the wire is determined by the length and wire tension.

When a force-summing device, in conjunction with the vibrating wire principle, creates the necessary displacement the pre-loaded wire is stretched and the frequency of oscillation increases. This resultant change in frequency is inversely proportional to a positive displacement^[G10].

Instrument sensitivity is strongly dependent on the thermal history of the vibrating element chosen, as shown in Figure 6.122^[V1]. A ribbon of tungsten approximately $0.00051 \times 0.0051 \times 1.448$ cm was used for all four test runs (a-d).

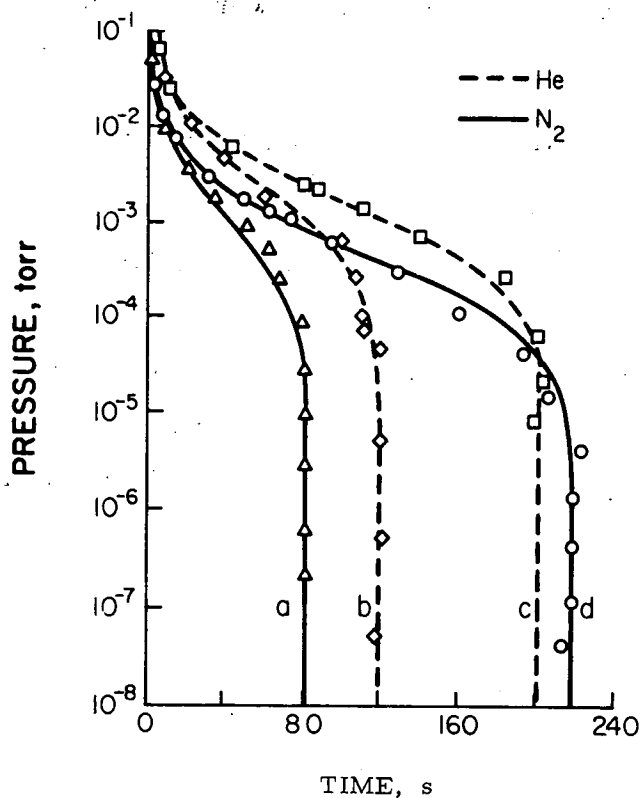


Figure 6.122 Sensitivity dependence on the thermal history of the vibrating wire element.

Test runs a-d were performed with the same ribbon after receiving various heat treatments and as shown the sensitivity and limiting value of decay time is different in each case. The differences between these runs

may suggest that the metallurgical state of the material has changed due to the heat treatment.

The over-all conclusion is that the vibrating wire (or ribbon) gauge is not significantly more sensitive than other gages of the same principle, but that it is rugged, easy to use, consistent with high vacuum, and presumably could be arranged to yield a continuous reading of pressure.

VIBRATING WIRE SPECIFICATIONS

Types of pressure measurement:

Gage (including vacuum), differential, or absolute.

Resolution:

Gage not significantly more sensitive than other gages of same principle, but is rugged, easy to use, and consistent with ultra-high vacuum. It can also be arranged to yield a continuous reading of pressure^[V1].

Vibration effects:

Very sensitive

Materials:

Wire generally used is tungsten.

Oxygen usage:

It is conceivable that vibrating wire pressure transducers can be used in gaseous or liquid O₂ environments. This is possible since only the force-summing element is exposed to the system being measured while the remaining parts are isolated.

Remarks:

As shown the sensitivity is questionable and transducer is very sensitive to shock and vibration.

Advantages:

1. High output.
2. Accuracy of receiving instrument may be high.
3. Carrier oscillator in FM/FM telemetering eliminated.
4. Output is frequency modulated.
5. Transmission of output frequency may be made over long distances with no loss in accuracy.
6. Rugged.
7. Easy to use.
8. Consistent with ultra-high vacuum.
9. Can be arranged to yield a continuous reading of pressure.

Disadvantages:

1. Largely non-linear.
2. Hysteresis errors high.
3. Stability is questionable.
4. Very sensitive to temperature change.
5. Shock sensitive.
6. Vibration sensitive.

6.13 OPTICAL

Optical pressure devices may employ either the "lever arm" or "fringe pattern" principle of operation. The former may incorporate a mirror acting as the diaphragm, or pressure sensing element, in conjunction with an incident light beam^[Op1]. Some distance from the mirror (which will determine the sensitivity) the light falls on a scale, and as pressure is applied to the system the light is deflected through an angle θ . It is this deflected angle which is then proportional to the applied pressure.

The "fringe pattern" method (an optical interferometric technique) is used for detecting rapidly varying pressures. In Figure 6.131 is shown the basic element which has been developed for pressure measurements^[Op2]. It consists of two basic parts, a diaphragm unit, having an optically flat face when unstressed, and an adjacent stator unit. The stator is generally made from fused quartz. The interior face of the stator is polished and slightly concave, having a large radius of curvature. The adjacent diaphragm is then polished optically flat and made totally reflecting.

When both the stator and diaphragm are then assembled it is evident from this construction that conditions are suitable for the formation of interference fringes when monochromatic light falls on the unit from the stator side. The resulting fringes are circular, however, only a narrow diametral strip of the fringe pattern is considered (by placing a mask containing a slit over the pattern).

The above technique can be monitored visually (after calibration) or a photographic method^[Op2], using a high-speed 35 mm camera, may permanently record the pressure changes on film to be analyzed later.

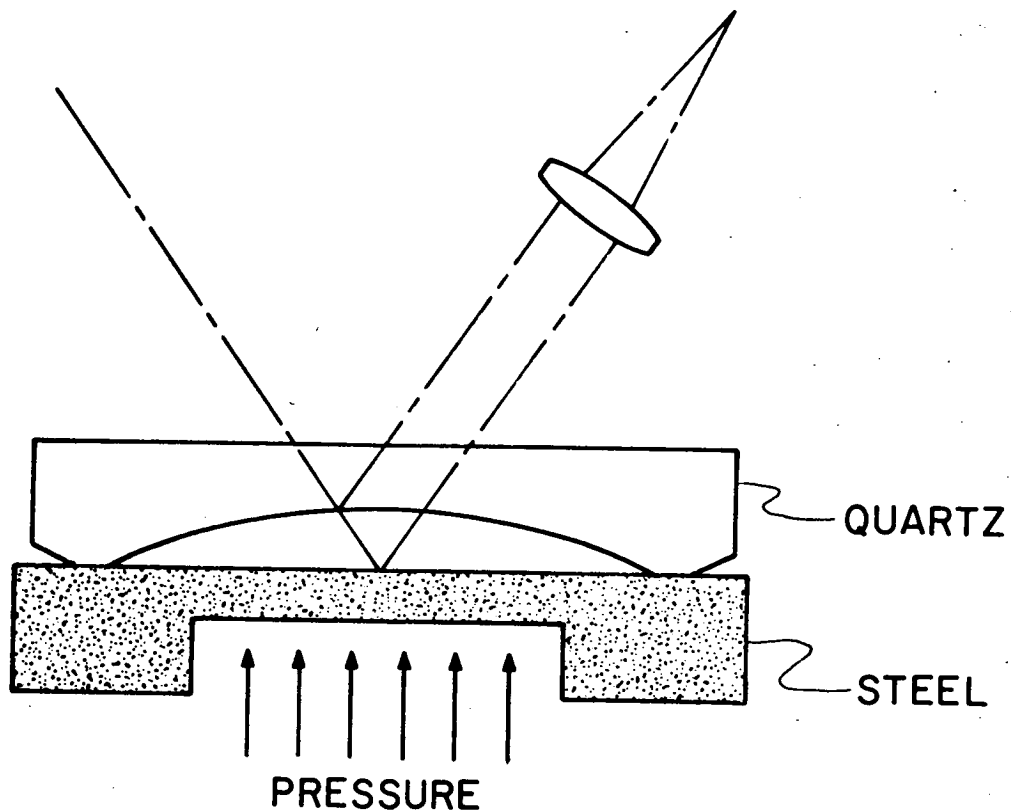


Figure 6.131 Schematic of a basic optical pressure sensing device.

OPTICAL SPECIFICATIONS

Types of pressure measurement (including base limitation for differential):

Gage (including vacuum).

Pressure ranges:

Approximately 0 to 5,000 psi.

Temperature (range, compensation, and stability):

Choice of materials will determine the thermal stability of the device. Fused quartz as the stator unit and proper mounting (to minimize the effect of thermal differences) will result in a temperature insensitive device. If the above is not followed the temperature coefficient of Young's modulus may affect the calibration by about 0.01 percent per degree centigrade. Also, a zero shift of approximately 0.025 percent of full scale per degree centigrade will be observed.

Calibration:

Straightforward. See "Calibration Techniques" (deadweight testers).

Vibration effects:

Very sensitive.

Materials.

The optical element may be quartz, glass, or other refractive material and for the choice of diaphragm material see the section on "Diaphragms."

Oxygen usage:

The optical pressure transducer should operate with gaseous O_2 at ambient temperature and not present any problem, but steps should be taken to prevent condensation on optical surfaces when cold gaseous or liquid O_2 are used.

Installation requirements and limitations:

The system is bulky which may severely limit installation.

Advantages:

1. Linear response.
2. Flat response from zero to very high frequencies (using a high-speed photographic technique ref. Op2).
3. Rugged.
4. Accuracy and pressure range can be high.
5. Using the photographic technique (ref. Op2) a continuous record for long time intervals may be made.

Disadvantages:

1. Very bulky.
2. Remote monitoring not possible.
3. Best for low and moderate frequency levels.
4. Installation can be difficult.

6.14 DIODE

It is well known that the tunneling current in Esahi diodes is sensitive to hydrostatic pressure changes^[Di2,Di3], and pressure gauges making use of this principle have been reported^[Di4]. The negative resistance region associated with the tunneling diode is undesirable for pressure transducer application. However, this can be formerly eliminated after the diode and its associated circuitry have satisfied the strict stability conditions of the amplifier mode of operation^[Di2].

Tunneling junction diodes, designed specifically for use as miniature pressure gages, have been fabricated from arsenic-doped germanium. These diodes have resistivities of ~ 0.001 ohm-cm and were tested under hydrostatic pressures of up to 10,000 psi^[Di2]. This type of diode pressure transducer is more desirable than the usual type since a negative region appears only at low temperatures. It also has the advantage that the strict stability requirements of the amplifier mode need not be met; furthermore, bulky low inductance mounting is not needed. With the above type (arsenic-doped) tunneling diode pressure transducer it is possible to fabricate the sensing element as small as 0.0076 cm in diameter.

Figures 6.141, 6.142, and 6.143 are typical of the circuitry and pressure vs frequency for a tunneling junction diode pressure transducer^[Di2].

Change in sensitivity when operating diode pressure transducers still remains a problem as Figure 6.202 illustrates. It shows the sensitivity to changes in temperature of an arsenic-doped germanium diode pressure transducer. The problem is characteristic of all semiconducting devices and must be corrected before the diode principle can be used for pressure transducers.

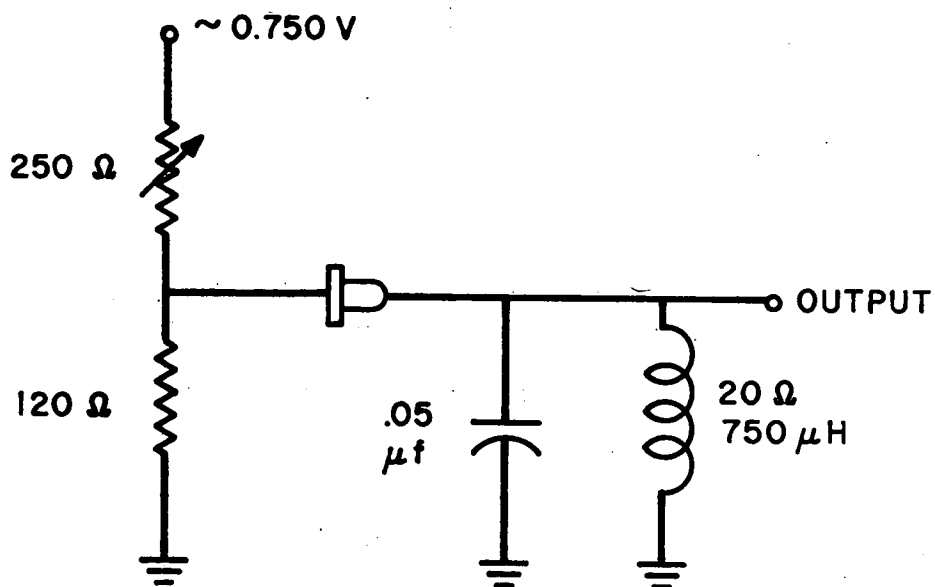


Figure 6.141 Tunnel diode oscillator.

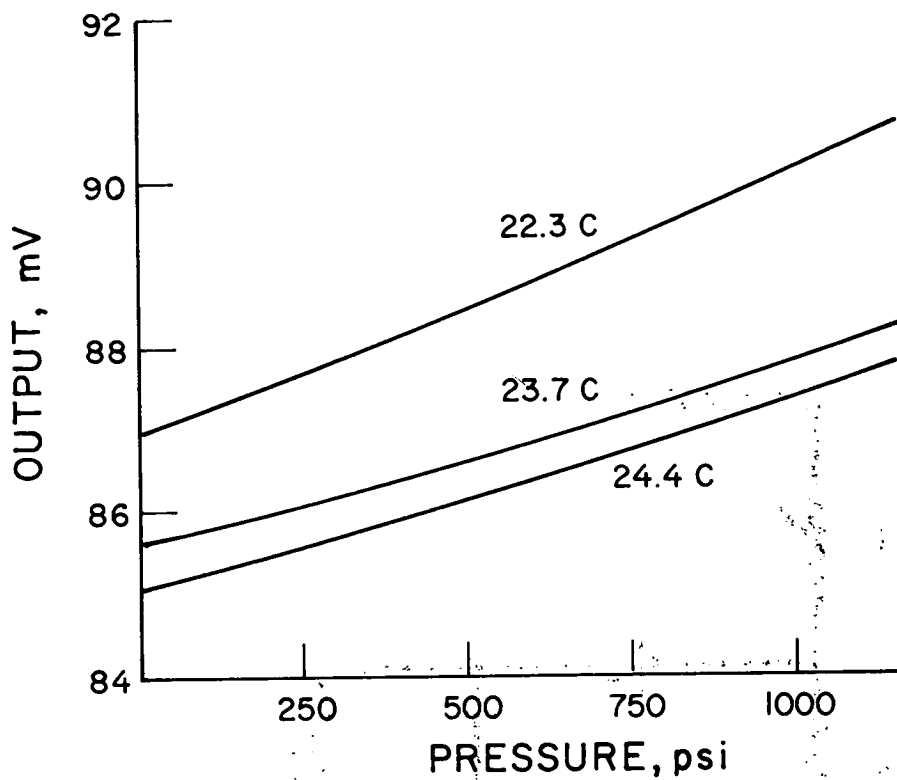


Figure 6.142 Diode output (mV) vs pressure (psi) at various temperatures.

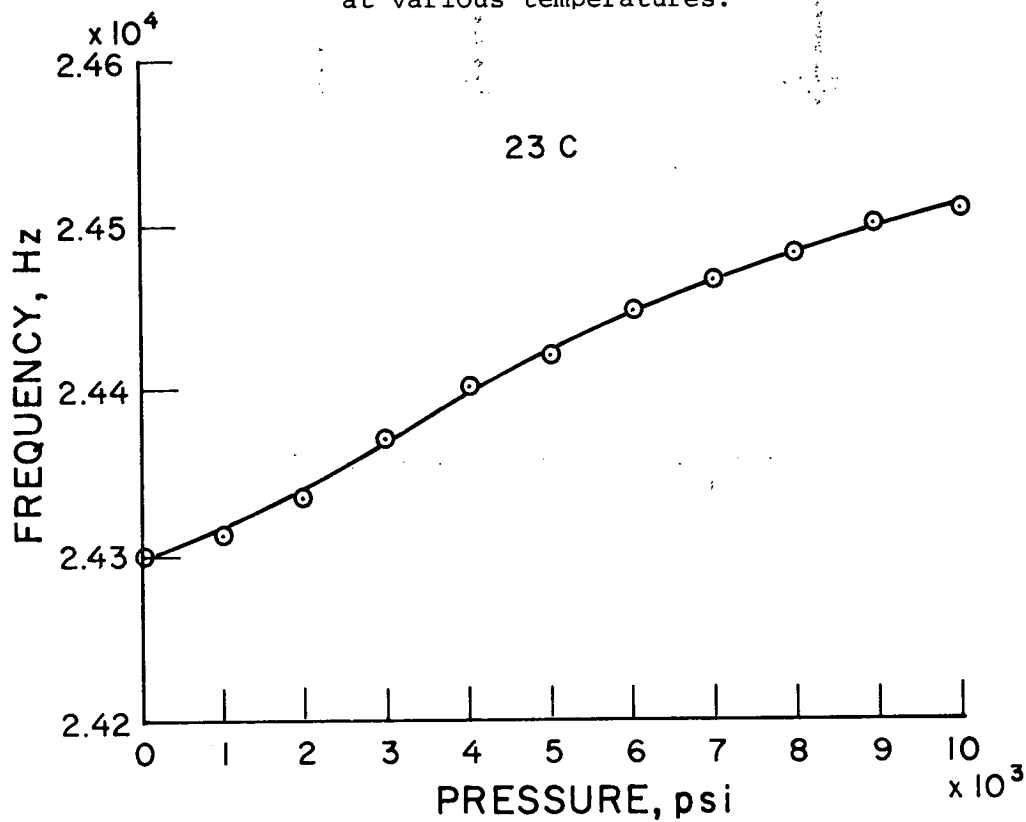


Figure 6.143 Diode frequency vs pressure.

DIODE SPECIFICATIONS

Types of pressure measurement (including base limitation for differential):

Gage

Pressure ranges:

~ 3.0 to 10,000 psi

Resolution:

Sensitivity greatest at lower pressures, ~ 4.4 mV psi⁻¹ at 1,000 psi and ~ 1.7 μ V psi⁻¹ at 10,000 psi.

Temperature (range, compensation, and stability):

Temperature sensitive (characteristic of all semiconductors).

Materials:

Arsenic-doped germanium, GaSb, InSb

Advantages:

- (1) Can be extremely small (approximately 0.0076 cm in diameter).
- (2) Inherent temperature sensitivity (characteristic of all semiconductors).

Disadvantages:

- (1) Some types require extremely stable amplifier modes. This factor could be costly.
- (2) The problem of sensitivity change caused by temperature differences is characteristic of all diode devices.

6.15 ELECTROKINETIC

The electrokinetic or streaming potential phenomenon is used as the basis for converting sonic to electrical energy. Williams^[E1] states that "...it was contemplated that the transducer would consist of a porous solid containing a fluid which, by oscillatory movement through the solid under sonic impulse, would generate an alternating current having the same frequency as the sonic impulse." Figure 6.151 illustrates a simplified version of the electrokinetic pressure transducer.

Leads, one on each side of the porous disc, are connected to a high-gain amplifier and then to an oscilloscope. "A small tuning fork having a frequency of about 300 Hz, held close to the diaphragm, yield a barely discernible signal on the oscilloscope at full gain of the amplifier..." [the amplifier used had a maximum gain of approximately 2000]". "When the handle of the fork was held against the diaphragm, a fairly large signal was observed on the oscilloscope. This signal, as well as that transmitted to the device through air, had the frequency of the vibrating fork and exhibited a sinusoidal wave form." [E1]

This type of pressure transducer, originally designed by an oil company, was used to measure the pressure fluctuations in a pipeline.

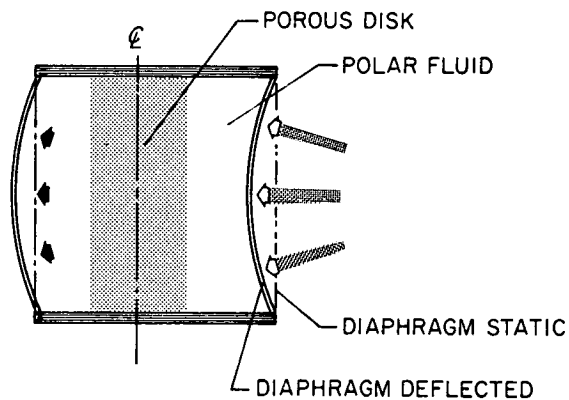


Figure 6.151 Electrokinetic pressure transducer.

ELECTROKINETIC SPECIFICATIONS

Types of pressure measurement (including base limitation for differential):

Dynamic gage (including vacuum)

Pressure ranges:

Limited only by diaphragm design (see "Diaphragm" section).

Temperature (range, compensation, and stability):

Operation not effected by small temperature changes and is stable.

Calibration:

Dynamic calibration must be made.

Vibration effects:

Very sensitive to vibration. Depending on if the mode of vibration is in or out of phase with the stream being measured will determine whether the effect is additive or subtractive.

Materials:

Stainless steel, glass, and lucite, polar fluid (often a volatile poisonous cyanide compound), fritted glass, and platinum leads.

Oxygen usage:

The electrokinetic pressure transducer may be suitable for use with ambient or cool oxygen. Oxygen near the liquid temperature will freeze the polar fluid and make its use impractical.

Installation requirements and limitations:

Unit is bulky.

Advantages:

1. High damping exhibited and no ringing frequency.
2. Frequency response high.
3. High output ($\sim 350 \text{ mV psi}^{-1}$).
4. Self-generating
5. Transducer is quite rugged.

Disadvantages:

1. Static pressure measurement not possible.
2. Accuracy of calibration limited because unit cannot be calibrated statically.
3. Zero-restoration poor.
4. Diaphragm distortion occurs with electrical bias.
5. Generally, the polar fluid used is a volatile, poisonous cyanide compound.

6.16 MAGNETOSTRICTIVE

The magnetic properties of a ferromagnetic material change when a stress is applied to the material. This phenomenon is known as magnetostriction. It can be used to convert mechanical effects into magnetic effects and vice versa. Figure 6.161 gives an example of how the basic principle of magnetostriction is used in a pressure measuring device.

Smith and Luxford^[M1] state that "...the magnetostriction effect varies greatly with the composition and heat treatment of the magnetic material. It is large in some nickel-iron alloys, some cobalt-iron alloys, and especially in pure nickel in the annealed condition". For pure nickel the magnetic properties change appreciably upon an application of moderate mechanical stress.

When the magnetostrictive pressure transducer is used in conjunction with a milliammeter, the device can only measure slowly varying pressures. To increase the frequency response, an indicating instrument capable of following a rapidly varying system must be used - e.g., a cathode ray oscillograph.

Hysteresis effects are common to all magnetic materials in varying degrees. Generally speaking, hysteresis is a minimum when the metal is in fully annealed gas-free condition, produced by vacuum annealing or annealing in hydrogen^[M1]. Hysteresis is undesirable in any measuring device and some method of minimizing its effects is essential to success.

Smith and Luxford go on to say "...the method used is to bring the metal to a standard magnetic condition by saturating it, that is, by the application of a magnetic field sufficiently strong to orient substantially all the magnetic elements in one direction. By use of an alternating magnetizing field, the metal may be brought to this standard condition as often as may be desired".

The heating effect of eddy currents induced in the metal by the alternating field must be minimized by the use of thin material, for example, thin walled tube, wire, or stampings.

The use of a pair of similar measuring elements in a symmetrical electrical circuit is desirable, since both elements change equally when conditions change and thereby a compensation is made.

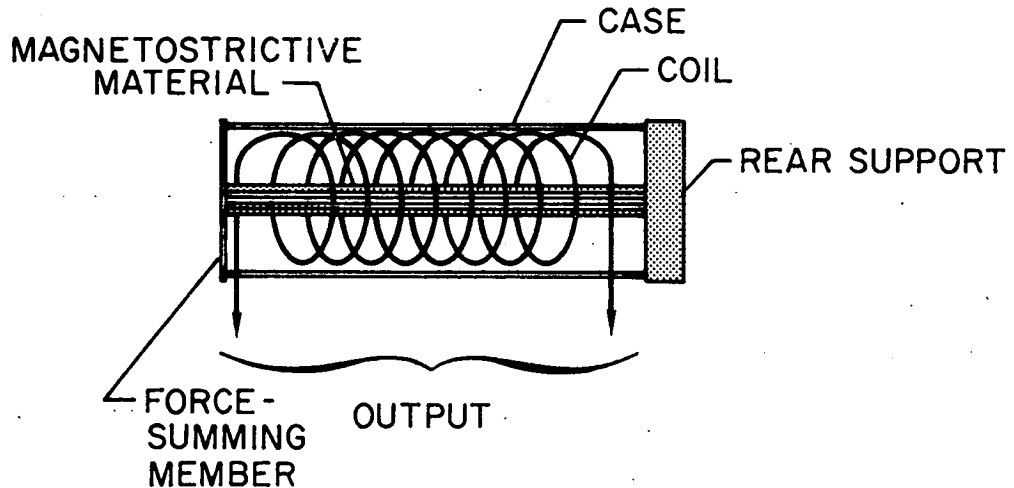


Figure 6.161 Magnetostrictive pressure transducer [G10].

Advantages:

1. Compact
2. Very reliable
3. Operation simple

Disadvantages:

1. Hysteresis. May be reduced by applying a strong alternating field continuously to annul the effects of previously applied stresses.

6.17 OHMSTRICTIVE

The ohmstrictive pressure transducer utilizes a pressure-sensitive powder (such as carbon or other conductor) or liquid between a force-summing element and a fixed plate. A simplified schematic of transducer design and electrical diagram is given in Figure 6.171.

As pressure is applied to the conductive force-summing element the resistance of the pressure-sensitive material changes. The operation of this type of device is similar to that of a carbon microphone.

In spite of its simplicity the operational principle has not been exploited sufficiently to allow a detailed discussion of its capabilities^[G10].

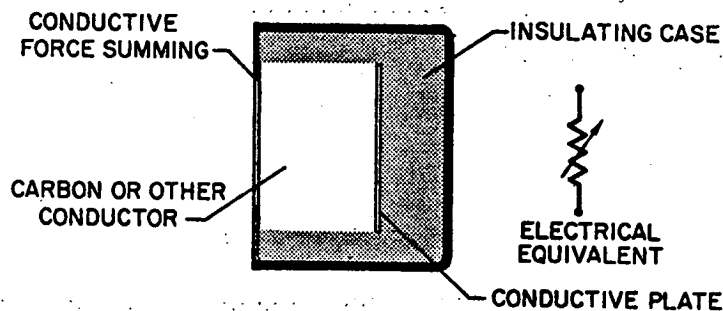


Figure 6.171 Ohmstrictive pressure transducer.

Advantages:

1. Can be used statically or dynamically.
2. Rugged.
3. Inexpensive.
4. High reliability.
5. High output.
6. Will operate at high frequencies.
7. Easy to manufacture and may be made small.

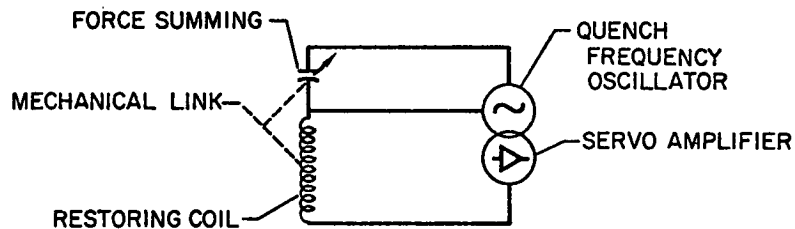
Disadvantages:

1. Without compensation may be thermally unstable.
2. Some inherent electrical noise.
3. Questionable repeatability.
4. Vibration sensitive.

6.18 FORCE-BALANCE

Although other basic principles may be used with this device, most applications employ either a capacitive or linear variable differential transformer element to sense the applied pressure. Figure 6.181 illustrates the electrical arrangement of the self-restoring force balance transducer.

The output of the sensing element is fed to an amplifier, which in turn feeds back a restoring force equal to the applied pressure. The sensing mechanism is then returned to its original position (by a servo) before the force was applied.



$$\text{BASIC FORMULA: } i = a \left(\frac{b_1 M}{b_2 n B} \right)$$

i = OUTPUT CURRENT THRU RESTORING COIL
 a = ACCELERATION
 b_1 = UNIT OF TORQUE FORCE
 b_2 = DIMENSIONAL CONSTANT
 B = MAGNETIC FLUX DENSITY
 M = UNBALANCE MOMENT

Figure 6.181 Force-balance pressure transducer.

Advantages:

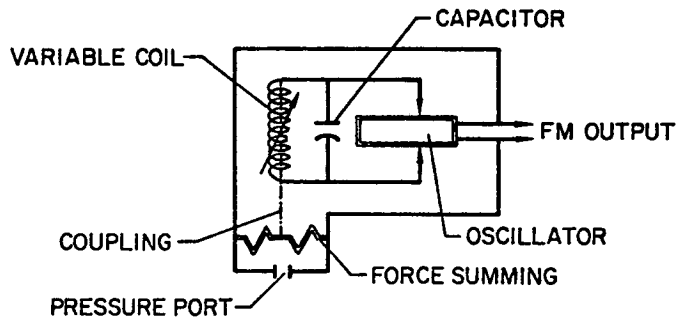
1. Measurements may be made statically or dynamically.
2. Accuracy good.
3. Stable.
4. Excellent resolution.
5. Output high.

Disadvantages:

1. Expensive.
2. Frequency response low.
3. Installation limited by its large size and weight.
4. Very sensitive to acceleration or shock.
5. Electrically complex.

6.19 OSCILLATING

"The frequency of a transistor oscillator is varied as a function of inductance or capacitance change in the force-summing member and associated transduction element"[G10]. The stability of the oscillator circuit in this type of pressure transducer is of prime consideration. Also, the temperature range of operation is currently restricted to the operating range of silicon transistors. Figure 6.191 illustrates the basic principle for oscillating transducers.



BASIC FORMULA: $\Delta f = f - f_0$

Δf = FREQUENCY DEVIATIONS

f = OPERATING FREQUENCY

f_0 = RESONANT FREQUENCY (No Force)

Figure 6.191 Oscillating pressure transducer.

Advantages:

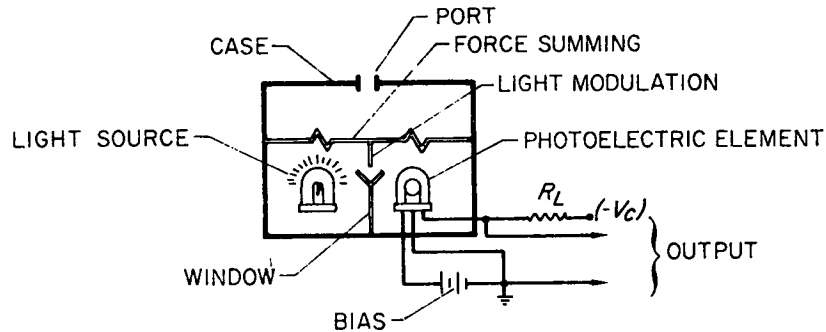
1. Small.
2. Dynamic or static measurements.
3. May be used for telemetering purposes.
4. High output.
5. Output may be shown as actual decimal unit counts representing applied pressure.

Disadvantages:

1. Temperature range limited.
2. Accuracy low.
3. High cost.
4. Special electronics required to provide analog information.
5. Low thermal stability.
6. Poor thermal zero shift.

6.20 PHOTOELECTRIC

The basic principle for photoelectric pressure transducers is illustrated in Figure 6.201^[G10].



BASIC FORMULA: $\Delta i_c = K(\mu a / ft \text{ candle}) - i_{c_0}$

i_c = COLLECTOR CURRENT

K = MODULATION CONSTANT

i_{c_0} = DARK CURRENT

Figure 6.201 Photoelectric pressure transducer.

A force-summing device such as the diaphragm, bellows, or Bourdon tube is used to modulate the light intensity incident upon a photosensitive element. This affects the photoemissive property of the element, and as a result the rate of change will be linear with displacement and also pressure. An important consideration to obtain transducer stability is by maintaining a light source which does not vary in intensity.

Advantages:

1. High output.
2. Construction can be simple.
3. Static and dynamic measurements may be made.

Disadvantages:

1. Large displacements are required.
2. Low frequency response.
3. Long-term stability can be poor.
4. Limited temperature range.

7. LOW-TEMPERATURE CALIBRATION METHODS

Pressure transducer calibration at cryogenic temperatures present special problems some of which depend on transducer type^[C1,C2,C5,C6]. Transducers such as strain gage, potentiometric, capacitance, inductance, reluctance, and piezoelectrics may be fabricated as sealed units for total immersion into the cryogenic medium for a more direct measurement of pressure. In this case, only the electrical leads are taken from the transducer to ambient conditions and therefore, heat leak is significantly reduced. All types mentioned above have their own operational characteristics when operated at low-temperature.

Other pressure transducer types (e.g., manometer, transport property, electrokinetic, etc.) may be difficult to calibrate or totally unsuitable for use at low temperature.

McLellan^[C7] indicates a method for calibrating pressure transducers down to 7 K with static pressures up to 2,000 psi. A schematic drawing of the system is shown in Figure 7.1. Unfortunately, no test data were given in the report; however, five transducers were said to have been calibrated successfully at 7 K without any problem.

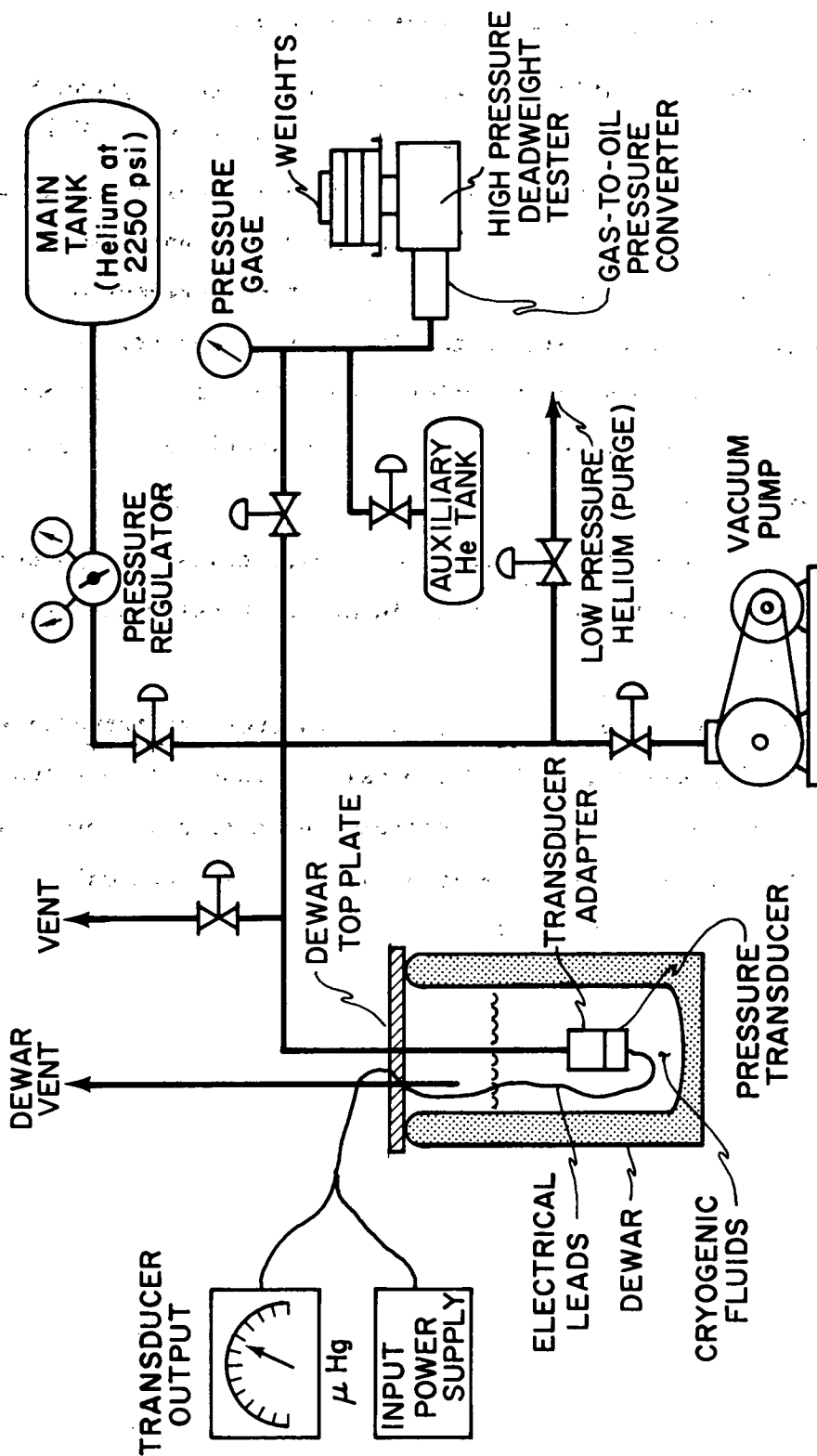


Figure 7.1 Cryogenic pressure transducer calibration system

8. CALIBRATION TECHNIQUES (OTHER)

8.1 DEADWEIGHT TESTERS

The deadweight tester, as the manometer, is also considered a primary standard for pressure measurement and is used for the calibration of less accurate gages or transducers. Depending on calibration pressure range, there are two basic types of deadweight testers. The first, schematically shown in Figure 8.11, is a low-range (0.3-1.5 to 1.5-500 psi) device which can measure gage or absolute pressure (by evacuation of the bell jar).

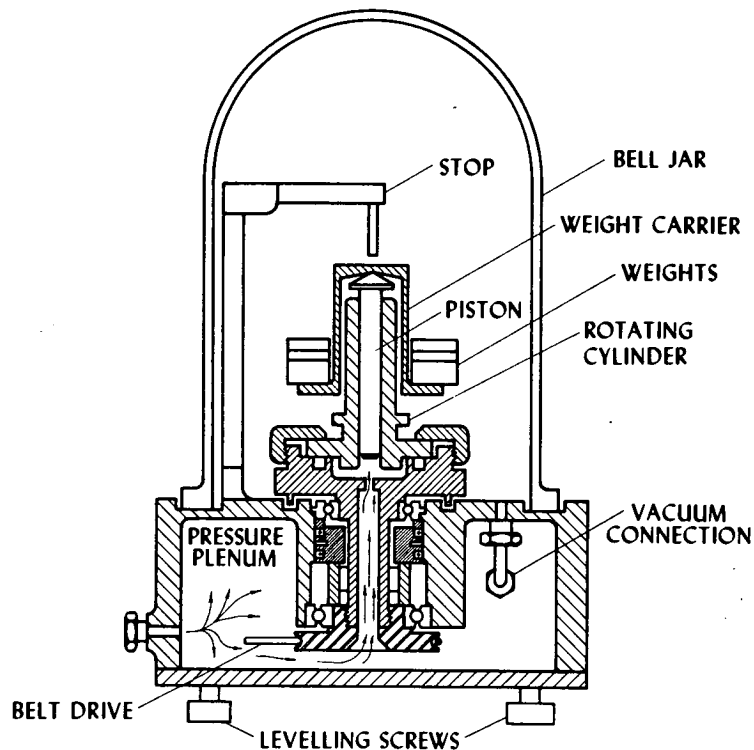
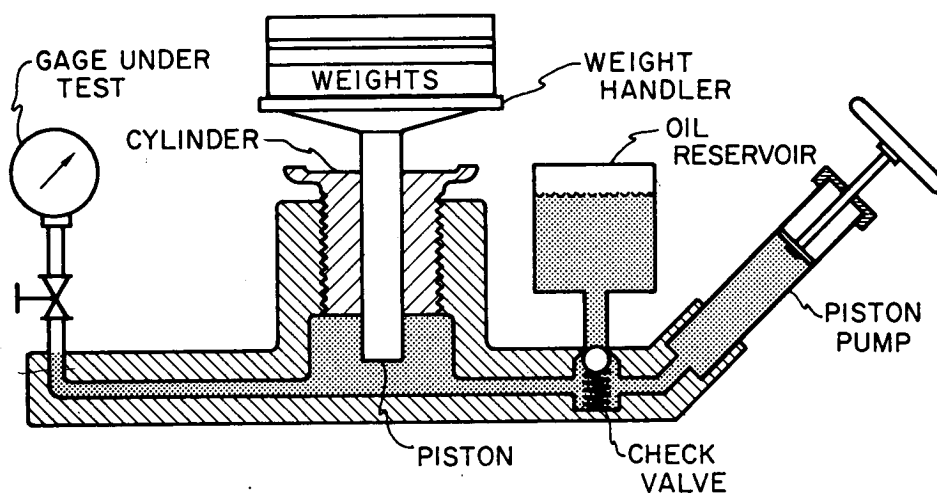


Figure 8.11 Low-pressure deadweight tester.

Where low pressures are used no special method is necessary to control the clearance between the piston and cylinder (with high-pressure deadweight testers this becomes an important factor).

The low-range device (shown in Figure 8.11) uses air as the working fluid. A source of clean, filtered, compressed air must be provided. The use of air is desirable, as it minimizes the head and buoyancy errors which require calculation of corrections if a liquid were used.

The high-pressure deadweight tester is shown in Figure 8.12 and differs from the low-pressure device in that a method for controlling the clearance between the cylinder and piston is used. Deadweight testers for use over 10,000 psi employ some special method to control the clearance between the piston and cylinder, to improve accuracy and prevent excessive leakage.



HIGH - PRESSURE DEADWEIGHT TESTER

Figure 8.12 High-pressure Deadweight Tester.

A high pressure oil chamber surrounds the cylinder and the oil pressure within is controlled by a secondary source of fluid pressure. When very high pressures are measured, fluid is pumped to the exterior chamber to compress it slightly and counteract the natural tendency of the cylinder to enlarge under the internal pressure being measured.

The piston in a deadweight tester is accurately machined and has a definite area such as $1/8$, $1/6$, $1/40$, or $1/80$ in². A platform is attached to the top of the piston and serves to hold the weights. The total pressure in the system (when balanced) is the combination of the weights, piston, and platform assembly divided by the cross-sectional area of the piston. To calibrate a gage, using the deadweight tester, the appropriate amount of weight is placed on the platform assembly and the system pressure is increased until it offsets the platform assembly weight. When this occurs, the platform, piston, and weights begin to "float". Friction in the system is minimized by slowly rotating the weight handler during calibration.

The deadweight tester may be operated using water instead of oil for the calibration of oxygen gages. However, the minimum pressures which may be measured are higher due to the poor lubricating quality of water. When water must be used, a small amount of soap added will improve the lubrication of the piston and cylinder assembly.

Oxygen and other gages which must be kept free from oil may be checked on a normal deadweight tester using oil if a water filled "U" tube (or other sealing device) is inserted between the gage and tester.

Cross^[C17] indicates that error in measurement results from failure to account for the parameters or from the uncertainty of the measured values of them. It is obvious that error results from the uncertainty of the mass of the loading weights and the measurement of the effective area of the piston and cylinder. Other sources of error may not be so easily recognized. Such sources include the air buoyancy on the weights, the fluid buoyancy on the piston, the value of local gravity, the force on the piston due to the

surface tension of the fluid, the thermal expansion and elastic deformation of the piston and cylinder, and the fluid heads involved. These effects can be evaluated and corrections applied to reduce the magnitude of overall error of measurement.

"Air buoyancy corrections amount to about 0.015 percent of the load. The corrections for the buoyancy of the pressure fluid on the piston have been found to range from zero to nearly 0.5 psi, and could be larger. The values of local gravity differ by over 0.3 percent at different places in the United States. The pressure correction due to surface tension is usually negligible, but may amount to more than 0.003 psi. Thermal expansion of the effective piston area is usually about 0.003 percent per °C and elastic distortion may amount to 0.05 percent at 10,000 psi. Fluid head amounts to about 0.03 psi per inch for lubricating oils"[G2,C17].

For a deadweight gage tester connected to a tight system, with the piston falling slowly because of the leakage of liquid past it, the effective area is the average of the cross-section of the piston and the area of the bore. This effective area is somewhat changed by temperature and the applied internal pressure (an important factor for high pressure measurement). The following table will help to illustrate temperature effect.

Material	Effective area increase PPM/°F
Carbon steel (piston and cyl.)	13
Stainless steel (piston and cyl.)	18
Carbon steel (piston) and brass (cyl.)	17

The distortion of piston and cylinder under pressure is greatly dependent on design and may either increase or decrease the effective area by as much as a part in ten thousand at 10,000 psi^[G2]. Wear and aging over a period of years will also change the dimensions of the piston and cylinder which generally results in irregular errors.

It usually happens that the point of measurement is at a different elevation than the lower end of the piston. Correction should, therefore, be made for the pressure difference due to the fluid head between these two points. The height is taken as positive when the gage is above the piston. When oil is used in the gage tester, the correction will be approximately 0.03 psi for each inch difference in level.

"When the submerged part of the piston is of uniform cross-section, no buoyancy correction need be applied. In some designs the piston is enlarged to provide a stop for its upward motion or to give increased strength. If these enlargements are submerged in liquid, a buoyancy correction is necessary. The buoyancy correction factor b is equal to the difference between the actual submerged length of the piston and the length of a piston of uniform cross-section and of equal submerged volume. With some designs it is not possible to observe the piston level and therefore not possible to determine the submerged volume. In such a case, it is necessary to determine the buoyancy correction by test. It will usually not exceed a few tenths of a psi" [G2,C17] .

Where accuracy of 0.25 percent is adequate, only the head error need normally be considered. But if maximum accuracy is required, all correction factors must be taken into consideration. The following working equations [G17] and Table 8.11 will be helpful for this purpose and include the correction for gravity, mass, effective area, head, and buoyancy. For more information on the equations given to compute the absolute or gage pressure in a system see reference C17.

$$P = p_p + H_{fp} + P_a$$

$$p_g = p_p + H_{fp} - H_a$$

$$H_{fp} = \rho_{fp} h_{fp} k g_L$$

$$H_a = - \rho_a h_a k g_L$$

$$A_o = \frac{A_k + A_c}{2} [1 + a(t_s - t_m)]$$

$$a = a_k + a_c$$

$$b = \frac{3\mu - 1}{Y}$$

$$M_{fa} = (A_e y_{fa} - V_{fa}) \rho_{fa}$$

$$A_e = A_o [1 + a(t - t_s)] (1 + b p_p) [1 + d(p_z - p_j)]$$

$$\Delta h = y_{fp} - \frac{V_{fp}}{A_e}$$

$$p_p = \frac{\frac{M_m}{A_o} \left(1 - \frac{\rho_a}{\rho_m}\right) k g_L + \frac{M_{fa}}{A_o} \left(1 - \frac{\rho_a}{\rho_{fa}}\right) k g_L + \frac{\gamma C}{A_o}}{[1 + a(t - t_s)] (1 + b p_p) [1 + d(p_z - p_j)]}$$

where

A_c Cylinder area.

A_e Effective area of piston.

A_k Piston area.

A_o Effective area of the piston at atmospheric pressure and temperature t_s .

C Circumference of the piston at the surface of the pressure fluid.

H_a Pressure difference in the atmosphere between the reference level of the piston gage and the reference level of the system to be measured.

H_{fp} Pressure head of the column of pressure transmitting fluid between the reference level of the piston gage and the reference level of the system to be measured.

M_{fa} Mass of the pressure fluid at atmospheric pressure contributing to the load on the piston.

M_m Mass of the loading weights, including the piston assembly.

- P Absolute (total) pressure.
- P_a Atmospheric pressure at the reference level of the piston gage.
- V_{fa} Volume of the submerged part of the piston above the cylinder.
- V_{fp} Volume of the part of the piston below the cylinder.
- Y Young's modulus.
- a Fractional change in effective area with unit change in temperature.
- b Fractional change in effective area with unit change in pressure.
- d Fractional change in area with unit change in jacket pressure.
- g_L Local acceleration due to gravity.
- h_a Height of the air column measured from the reference level of the piston gage to the reference level of the system. Measurements up from the piston gage reference level are positive.
- h_{fp} Height of the column of pressure fluid measured from the reference level of the piston gage to the reference level of the system. Measurements up from the piston gage reference level are positive.
- Δh Height of the reference level of the piston gage with respect to the bottom of the piston. Measurements up from the bottom of the piston are positive.
- k Proportionality factor relating force, mass and gravity.
- P_g Gage pressure.
- P_j Jacket pressure.
- P_p Pressure measured by piston gage at the reference level of the piston gage.
- P_z Jacket pressure required to reduce the piston-cylinder clearance to zero.
- t Temperature of the piston gage.
- t_m Temperature at which piston and cylinder are measured.
- t_s Reference temperature (usually the nominal room temperature).

y_{fa} Length of the submerged part of the piston above the cylinder.
 y_{fp} Length of the part of the piston below the cylinder.
 α_c Temperature coefficient of linear expansion of the cylinder.
 α_k Temperature coefficient of linear expansion of the piston.
 γ Surface tension of the pressure fluid.
 μ Poisson's ratio for the piston.
 ρ_a Mean density of the air displaced by the load.
 ρ_{fa} Density of the pressure fluid at atmospheric pressure.
 ρ_{fp} Density of the pressure fluid at pressure P.
 ρ_m Density of the weights.

TABLE 8.11

GRAVITY VS LATITUDE

(Based on Standard Gravity & International Gravity Formula)

$$g_s = 980.665 \text{ cm/sec}^2$$

$$z\varphi = 978.0490 (1 + .0052884 \sin^2\varphi - .0000059 \sin^2 2\varphi)$$

φ	$g\varphi \text{ cm/sec}^2$
0	978.0490
5	978.0881
10	978.2043
15	978.3941
20	978.6517
21	978.7107
22	978.7721
23	978.8356
24	978.9015
25	978.9693
26	979.0394
27	979.1113
28	979.1850
29	979.2606
30	979.3378
31	979.4165
32	979.4968
33	979.5785
34	979.6614
35	979.7455
36	979.8308
37	979.9170
38	980.0041
39	980.0919
40	980.1805
41	980.2696
42	980.3592
43	980.4489
44	980.5391
45	980.6294
45°23.670'	980.66500
46	980.7197
47	980.8097
48	980.8998
49	980.9894
50	981.0787
55	981.5146
60	981.9239
65	982.2941
70	982.6139
75	982.8733
80	983.0646
85	983.1818
90	983.2213

Tolerances on the weights and effective diameter must be maintained to minimize error in the total tester. The following two tables set the tolerances to insure a total error of 0.10 percent or less for the system^[G2].

Table 8.12 Effective diameter.

Area, in ²	Effective diameter, in	Tolerance, in
1/8	0.398942	± 0.000100
1/16	0.282095	± 0.000070
1/40	0.178412	± 0.000040
1/80	0.126157	± 0.000031

Table 8.13 Weight tolerance.

Weight, oz	5	10	20	40	100
Tolerance, oz	± 0.0025	± 0.005	± 0.010	± 0.020	± 0.050
Pressure value in psi when used with an area of:					
1/8 in ²	2.5	5	10	20	50
1/16	5.0	10	20	40	100
1/40	12.5	25	50	100	250
1/80	25.0	50	100	200	500

In Figure 8.13 is a simplified block diagram which typifies the components necessary for a low-pressure deadweight calibration system.

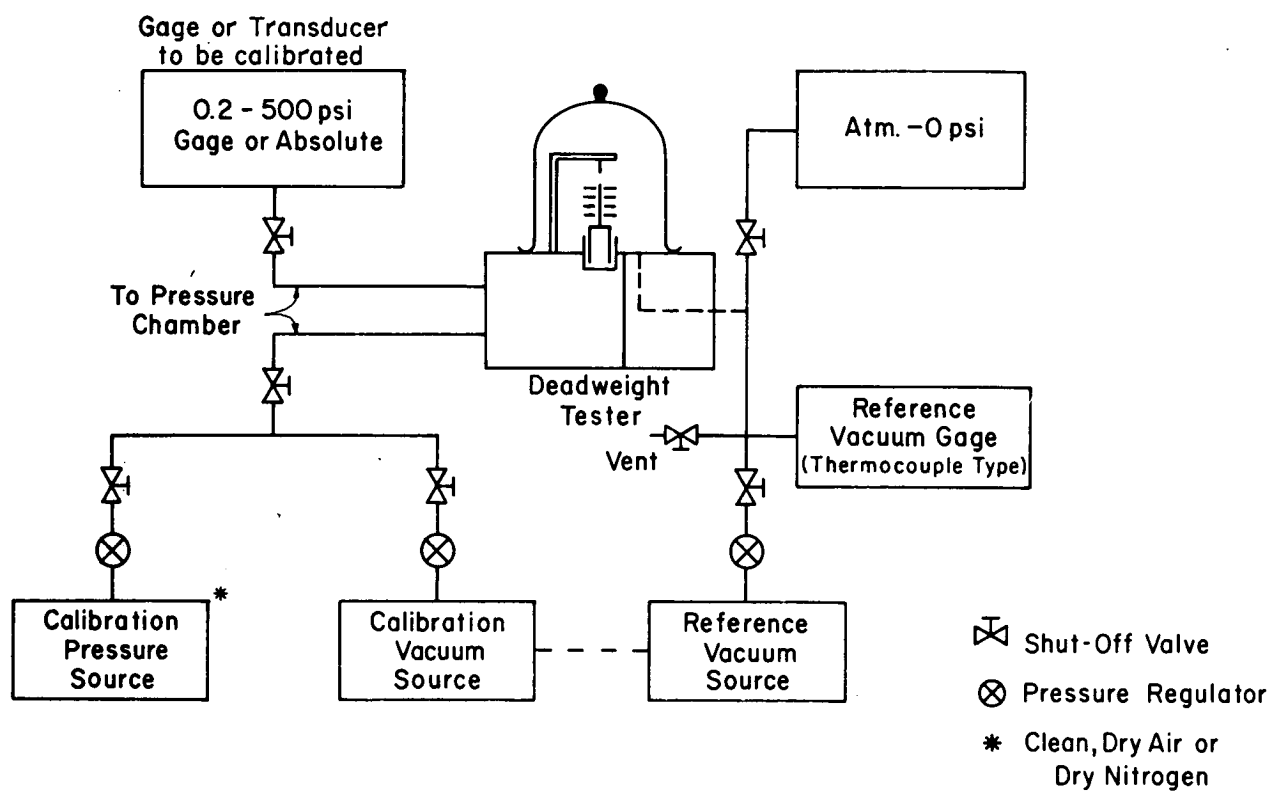


Figure 8.13 Typical deadweight tester system.

Each of the following sections, on the dynamic calibration of pressure transducers, 8.2 to 8.7, are covered briefly in this report due to the lack of information in the literature with respect to oxygen service. Their basic principle, nevertheless, for pressure transducer calibration may be ideally suited for a given low-temperature system. References furnished in section 9 on calibration methods^[C1-C8] will be very helpful for anyone wishing to pursue the subject further.

8.2 SHOCK TUBE

"A Shock tube, in its simplest form, consists of two sections of tubing separated by a thin diaphragm. When these two sections are pressurized to different pressure levels and the diaphragm is suddenly ruptured, the higher pressure gas will immediately begin to flow into and compress the gas at lower pressure" [C9]. Figure 8.21 illustrates a typical shock tube arrangement for calibrating pressure transducers.

The shock wave, as it continues to move downstream through the tube, is well-formed after a distance of approximately 10 to 15 tube diameters, after which, the wave continues to progress at a constant velocity. Behind the shock wave the pressure suddenly rises resulting in a positive pressure step. The shock tube's rise time between pressure levels is typically on the order of 10^{-9} s. The shock tube is commonly referred to as a step-function generator and should be able to change the pressure from one level to another in short enough time to shock excite high-frequency pressure transducers. High mach numbers may be obtained by using properly selected gases in the shock tube chambers. Also, by heating the compression chamber and cooling the expansion chamber an increased mach number may be realized.

"When a shock tube is utilized for pressure transducer calibration, several parameters must be measured before the amplitude of the pressure step can be ascertained. These parameters include the shock wave velocity, V_s , and the initial absolute pressure, P_1 , and temperature, T_1 , of the gas in the low pressure section" [C9].

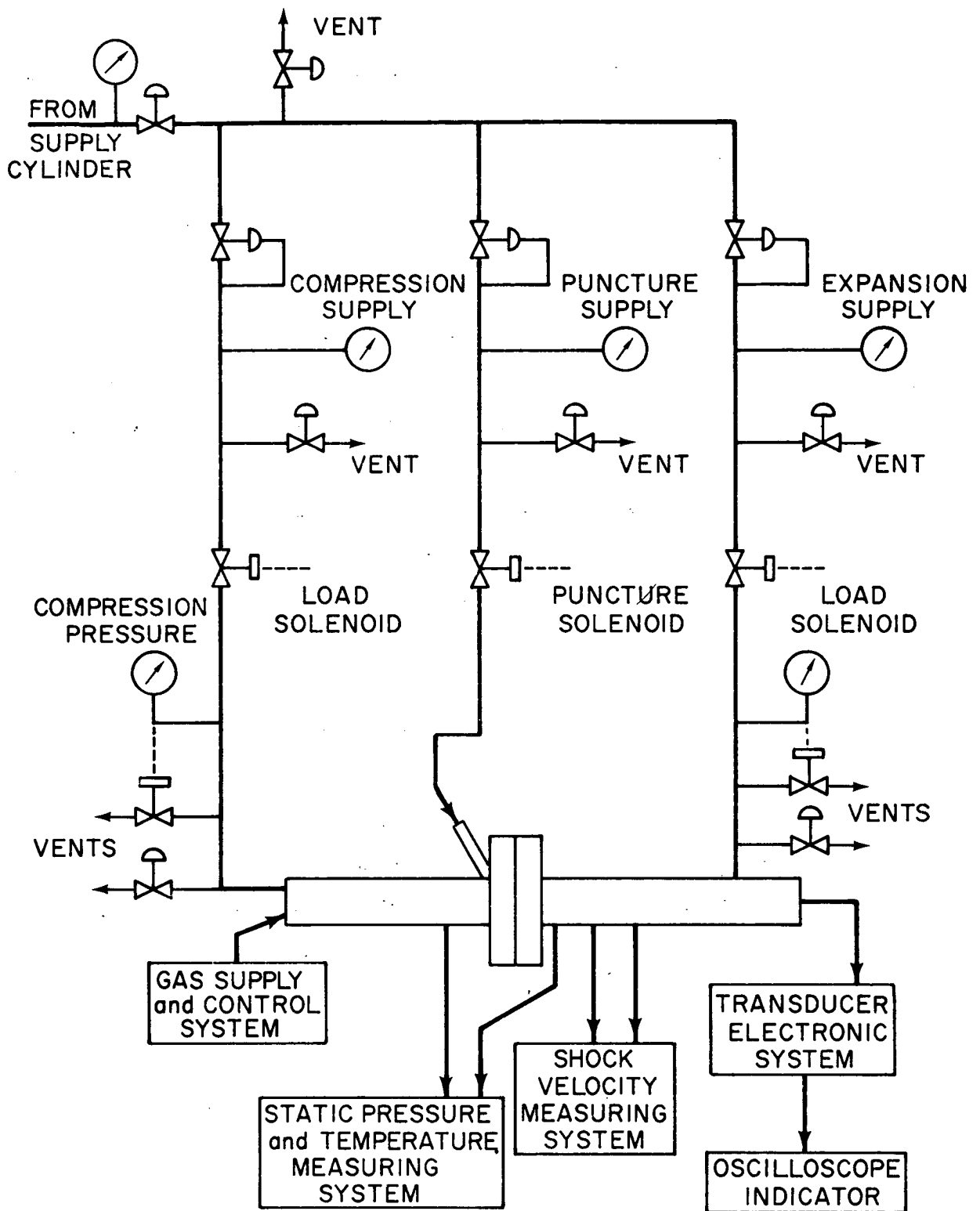


Figure 8.21 Shock tube calibration system.

8.3 SIREN

The siren technique for calibrating low and medium pressure transducers utilizes a siren-tuned-cavity oscillator for generating periodic (but not necessarily sinusoidal) pressure waves^[C10]. Figure 8.31 shows the basic components of the system. The essential elements of the siren-tuned-cavity generator are a cylindrical chamber with an axial orifice in one end and a revolving disc having a number of equally spaced holes arranged around its periphery. The wheel is positioned as shown in Figure 8.31 and rotated to interrupt the flow of air from an axial hole in the tuned-cavity. As a result, periodic pressure waves are generated with a waveform which is typical to that shown in Figure 8.31.

Two adjustments are necessary in order to operate the generator effectively. For each rotational speed of the siren (perforated disc) and the number of holes in that disc a pressure wave frequency will be produced. When the length of the cylinder is adjusted such that it acts as a half-wave resonator the pressure wave is reinforced and the amplitude at the transducer is determined.

"For purposes of calibration, the value of pressure at the cavity-transducer interface is measured with a previously calibrated transducer, or it is computed using methods described by Oberst^[C15]. When measured pressures are used as a standard, the calibrated gage must be an instrument with a uniform frequency response up to frequencies several times higher than the test frequency"^[C10].

Using this device peak pressures of up to 30 psi are possible with pulsation rates of from 50 to 1000 Hz.

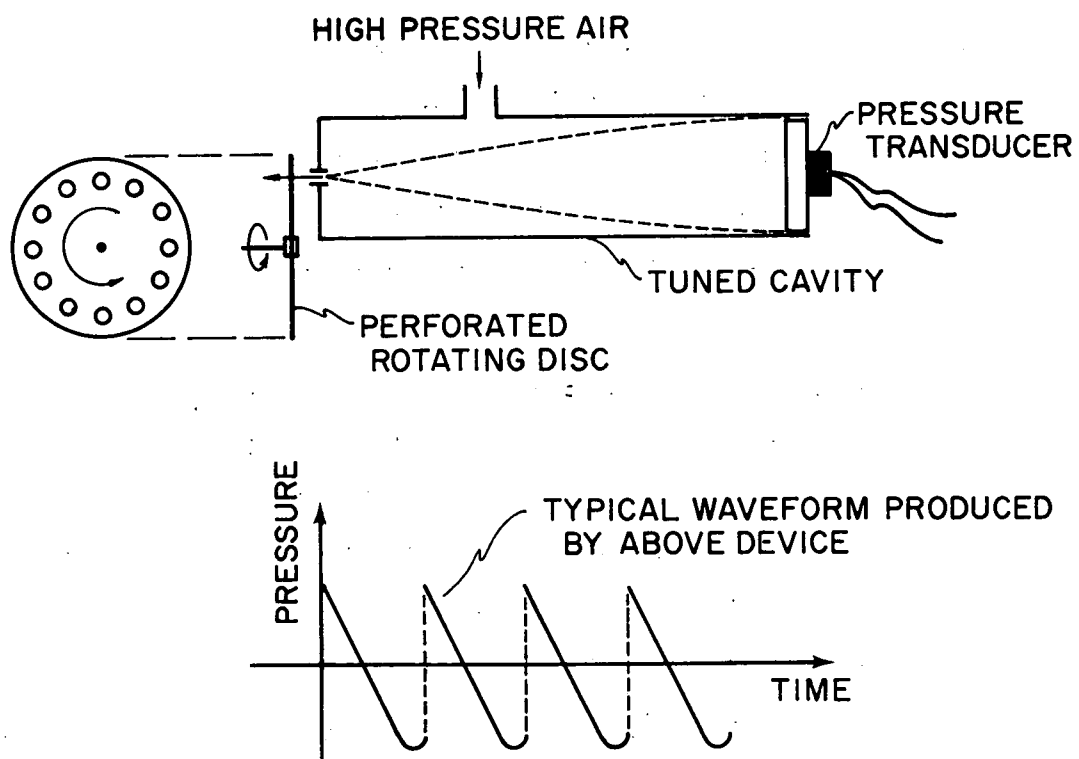


Figure 8.31 Siren-tuned-cavity generator.

8.4 ROTATING-VALVE GENERATORS

A forcing function with precisely controlled repetitive pressure pulses is sometimes necessary for the calibration of certain pressure transducers. A schematic representation of the mechanical device which generates such a pressure pulse is shown in Figure 8.41. Also, in the same figure, a typical wave form is shown with the average time between pulses on the order of 10^{-1} seconds. The device generates pulses at relatively low frequencies and levels of pressure may be precisely preset by means of pressure gages. By adjusting the speed of the driving motor, and consequently that of the rotation valve, a desired pulse repetition rate may be obtained. At higher repetition rates pressure steps may become distorted due a resonant effect created by the inertia of the gas column in the system. Therefore, this device is limited to operational frequencies below which the resonant effect is observed.

Schweppe^[C10] says that "Normally, the square pressure pulses generated by the rotating-valve device are not truly shock waves. Unlike the short-term, high intensity pulses generated by the acoustical-shock generator, the pulses from the rotating-valve generator are of longer duration (say, about 100 msec as compared to 250 μ sec) and lesser intensity (say, about 10 to 15 psi per step as compared to 200 psi).

"A major disadvantage of the rotating-valve generator is the presence of the relatively long tube between the transducer under test and the rotating-valve mechanism. In effect, it introduces a half-wave resonator into the calibration system which limits the effectiveness of the generator at high frequencies".

Another version of the rotating-valve generator produces a step-function pressure wave form as shown in Figure 8.42. This may be accomplished by proper design of the rotating valve such that several ports (both inlet and outlet) provide various individual inlet pressures with each having a unique axial orientation (each corresponding to a step in pressure)^[C10].

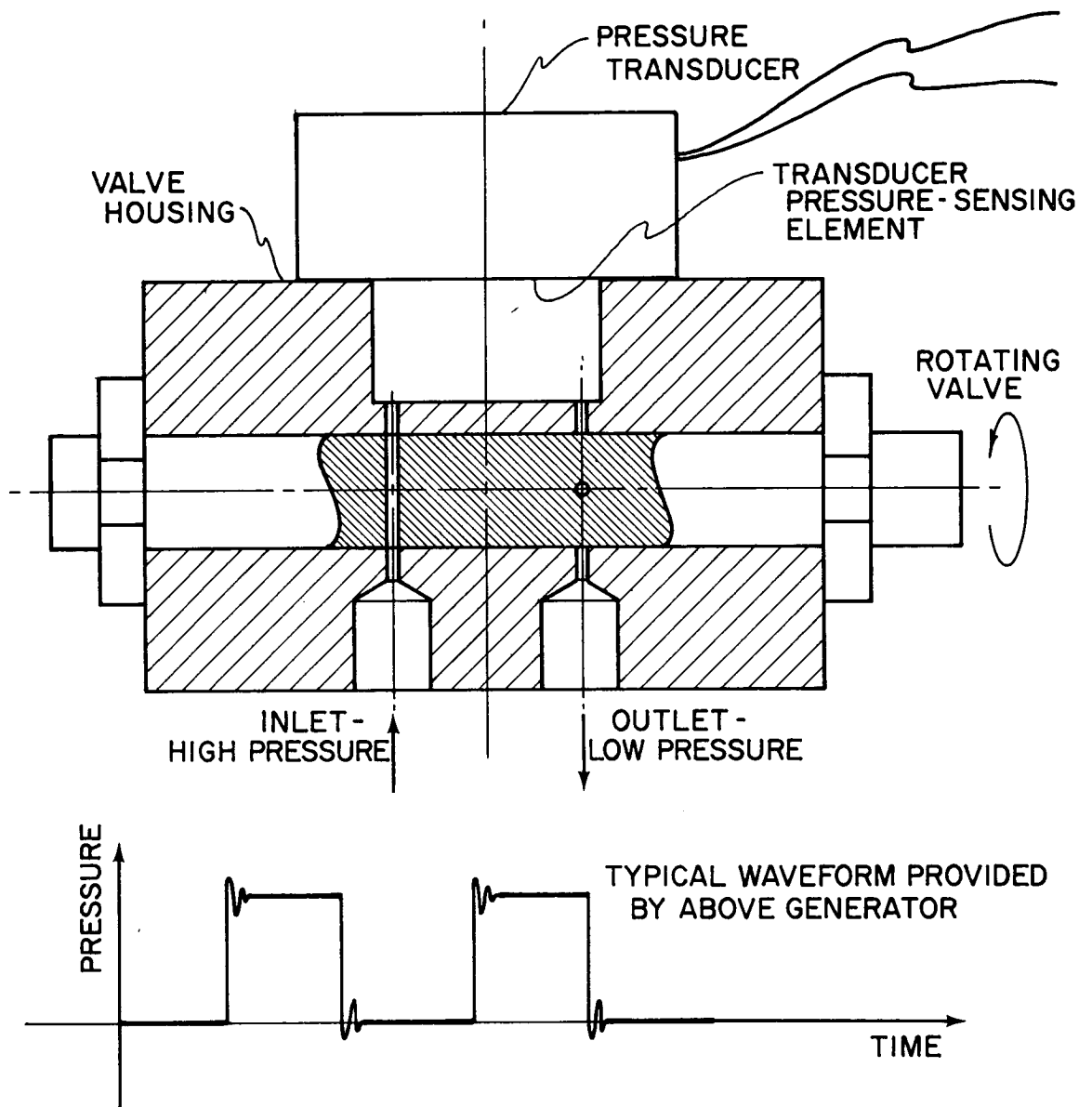


Figure 8.41 Rotating-valve pulse-function generator.

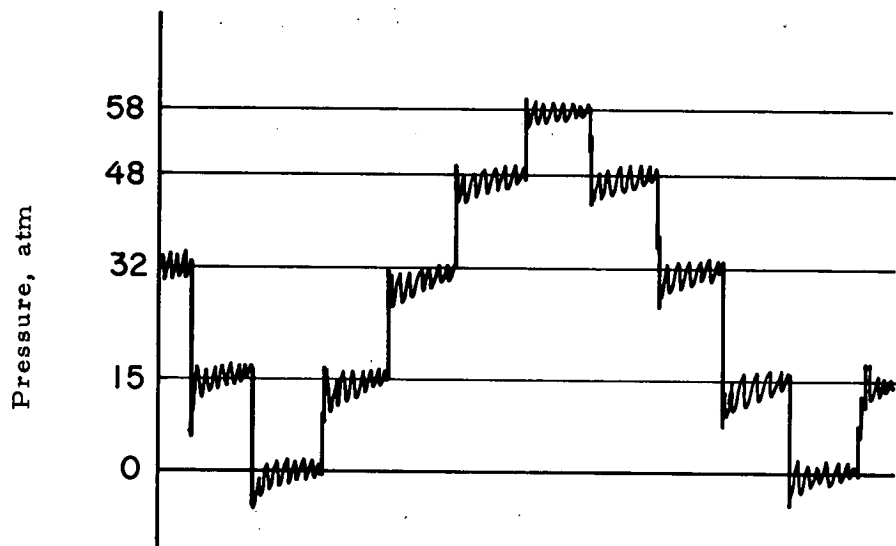


Figure 8.42 Rotating-valve step-function wave form.

8.5 LOW-FREQUENCY PNEUMATIC SINUSOIDAL GENERATOR

The pneumatic sinusoidal generator schematically shown in Figure 8.51 and was primarily designed for low-frequency, low-amplitude calibration. The obvious way to produce a sinusoidal pressure variation is by using a piston-in-cylinder device. A piston-in-cylinder generator when operated at high frequency and high amplitude produce pressure waves which are characterized by nonlinear effects [C10].

The motion of the piston is sinusoidal with a frequency of w (where $w = 2\pi f$) and the gas in the tube is assumed to behave ideally (where $P = \rho RT$).

Nominally, the output of a low-frequency pneumatic sinusoidal generator is in the range from 5 to 25 psi, but different ranges may be obtained by adjusting the operating stroke of the piston.

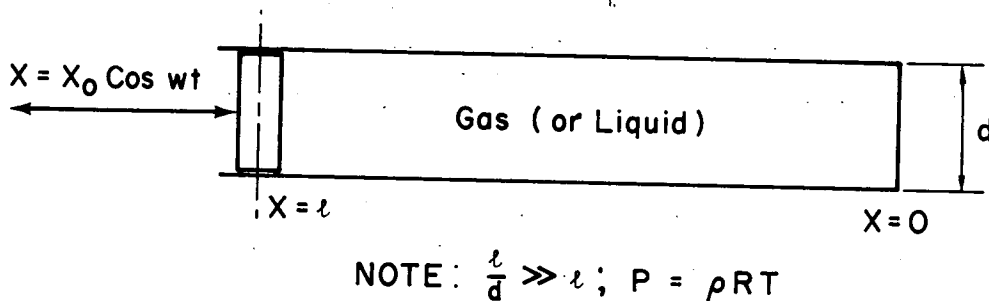


Figure 8.51 Low-frequency pneumatic sinusoid generator (piston-in-cylinder model).

8.6 ELECTROMAGNETIC METHODS

Electromagnetic methods for pressure transducer calibration may be used on devices which have diaphragms of magnetic material. The simplified schematic shown in Figure 8.61 illustrates the way in which a direct-excitation technique displaces the diaphragm (using a solenoid). Diaphragm assembly damping can be sensed and measured accurately to determine decay-rates and from these decay-rate measurements, the logarithmic decrement can be computed directly.

Schweppe^[C10] indicates that "By exposing the pressure-sensitive diaphragm to the atmosphere, the oscillatory motion of the transducer produces a corresponding pressure variation on the sensing element. The absolute movement of the diaphragm can be sensed and measured optically (at low frequencies) or by a capacitance pickup (shown in Figure 8.61). The frequency range over which this method has been used is reported to be 3,000 Hz under normal conditions and, with special equipment, 8,000 Hz^[C16]. Pressure levels are low (usually no more than 50 to 60 psi).

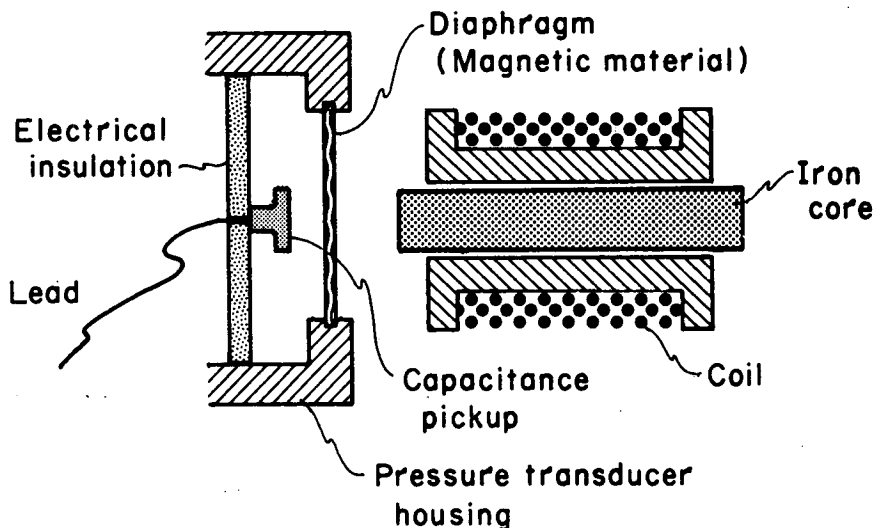


Figure 8.61 Arrangement for calibration using the electromagnetic technique.

8.7 HYDRAULIC SINUSOIDAL

The hydraulic sinusoidal generator is similar to the low-frequency pneumatic sinusoidal generator discussed in section 8.5; the only difference being a liquid is used as the active medium instead of gas^[C10]. The apparatus used is basically the same as the pneumatic sinusoidal generator shown in Figure 8.51. Principally, the differences between gas-and-liquid-piston-in-cylinder devices are associated with the incompressibility of liquids.

9. RECOMMENDATIONS

Data in the literature covering pressure transducer behavior at cryogenic temperatures are extremely limited, and in many cases not well documented. Therefore, an accurate evaluation is not possible.

Many pressure measurements are currently being made in low temperature systems; however, these are generally performed with the transducer at room temperature and connected to the system via piping. Using this method for pressure measurement, as one might expect, can greatly affect the accuracy and frequency response of the device, particularly if long lines with small diameters are used. In addition, where several transducers at various locations in a system are necessary the total heat leak due to the instrumentation lines may be large. For problems of this type refer to the sections on "Cryogenic Pressure Measurement and Pressure Tap Connections".

Transducers, at low temperature, usually experience one or more of the following; a change in sensitivity, a zero shift, an erratic performance (including non-linear behavior), or a complete failure. Smelser^[G57] performed tests on capacitance, potentiometric, and strain gage (both bonded and unbonded) pressure transducers at ambient conditions (298 K), at LN₂ (77 K), and at LH₂ (20 K). It was his conclusion that "...judging among the samples included in this series of tests, it appears that the unbonded strain gage will give the most satisfactory results at cryogenic temperatures. With the unbonded strain gage, measurements with an accuracy comparable to that obtainable at room temperature appear possible, if the instrument is used over a reasonable temperature span, and if the calibration is checked each time the instrument is cooled down. However, in a situation where large transient temperature excursions are experienced, as in the cooldown of a transfer line, their use would be questionable because of the possibility of large transient errors.

"The potentiometer type also appears to be quite useful. The best of the two tested showed more thermal cycling effects than the unbonded strain gage,

but no tendency to produce transient errors during rapid cooling was observed. A calibration check each time the instrument is cooled down would assure the best results".

Hayakawa^[G59] in a similar study found no transducer capable of performance predictable within 2 percent. Therefore, it is highly recommended that additional work be done on evaluating other transducer types, other methods of construction as well as retesting of transducers tested in the earlier programs. Once a firm, well documented, state of the art base has been established experimentally then any additional work necessary would be more clear. Without a firm base there is a high probability of wasted effort in future work in this area.

A cryogenic calibration system with varied capabilities is essential for the successful completion of such a program described above. In response to a request from the National Aeronautics and Space Administration (Marshall Space Flight Center, Huntsville, Alabama) a pressure transducer calibration facility has been constructed to statically and dynamically calibrate pressure transducers at cryogenic temperatures. Static calibrations will be made at pressures up to 10,000 psi. In addition, a dynamic calibration can be performed by superimposing cyclic fluctuations (from 0-10 psi and 1-100 Hz) upon any pre-selected base pressure to 10,000 psi. The versatility of such a system will lend itself to document more fully the performance of pressure transducers at low temperature.

The following is a brief description of the facility and Figure 9.1 shows the basic principle of operation. The temperature range for calibrating pressure transducers will be from 298 to 77 K initially but can be extended to 4 K if necessary. Electromagnets were designed to fit within the upper chamber of the apparatus and the volumetric change in each cell is created by the displacement of a bellows (see Figure 9.2). The two pressure cells, each having nominally the same dimensions, are joined with an intermediate

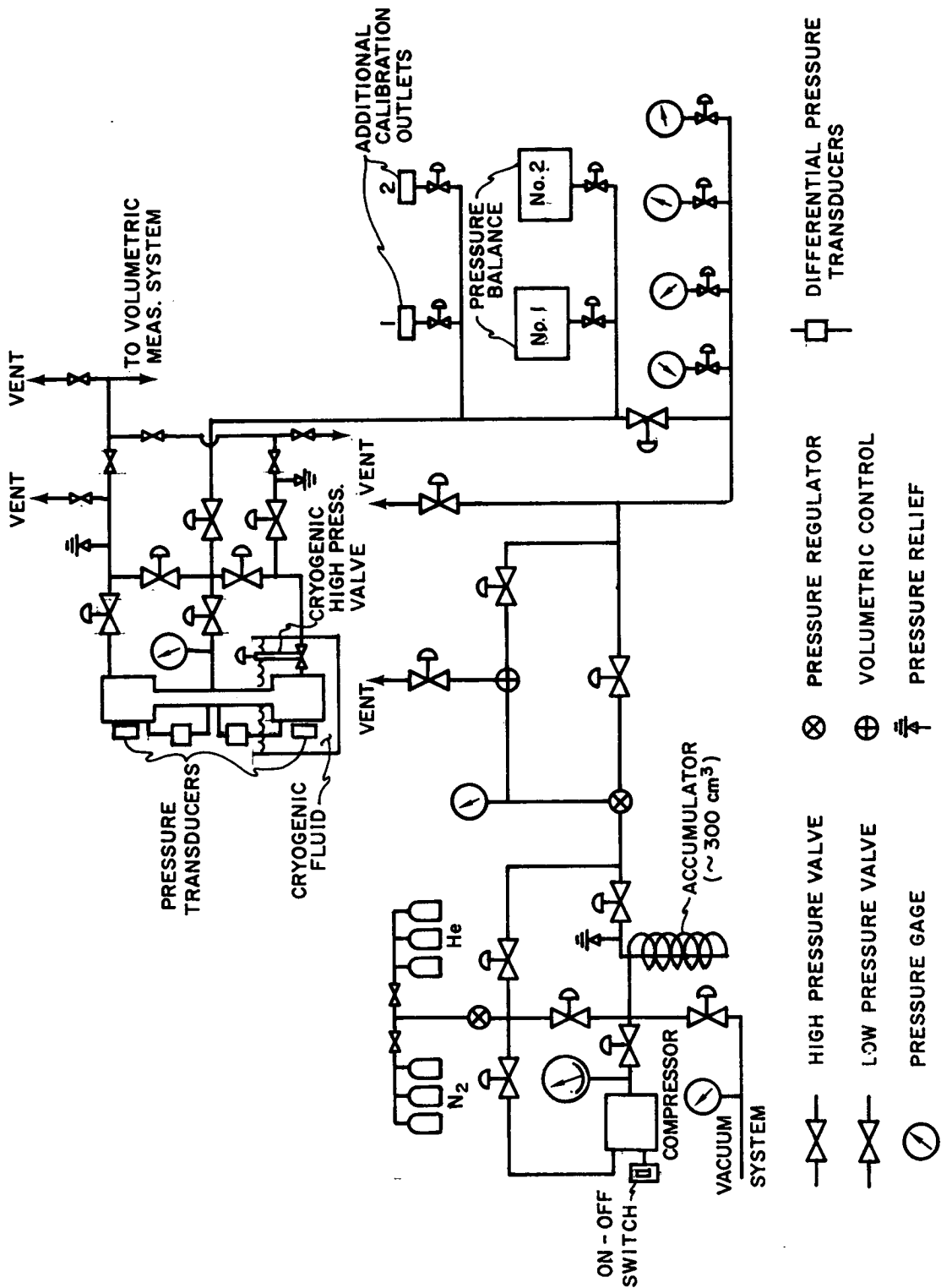


Figure 9.1 Static and dynamic cryogenic pressure sensor test facility.

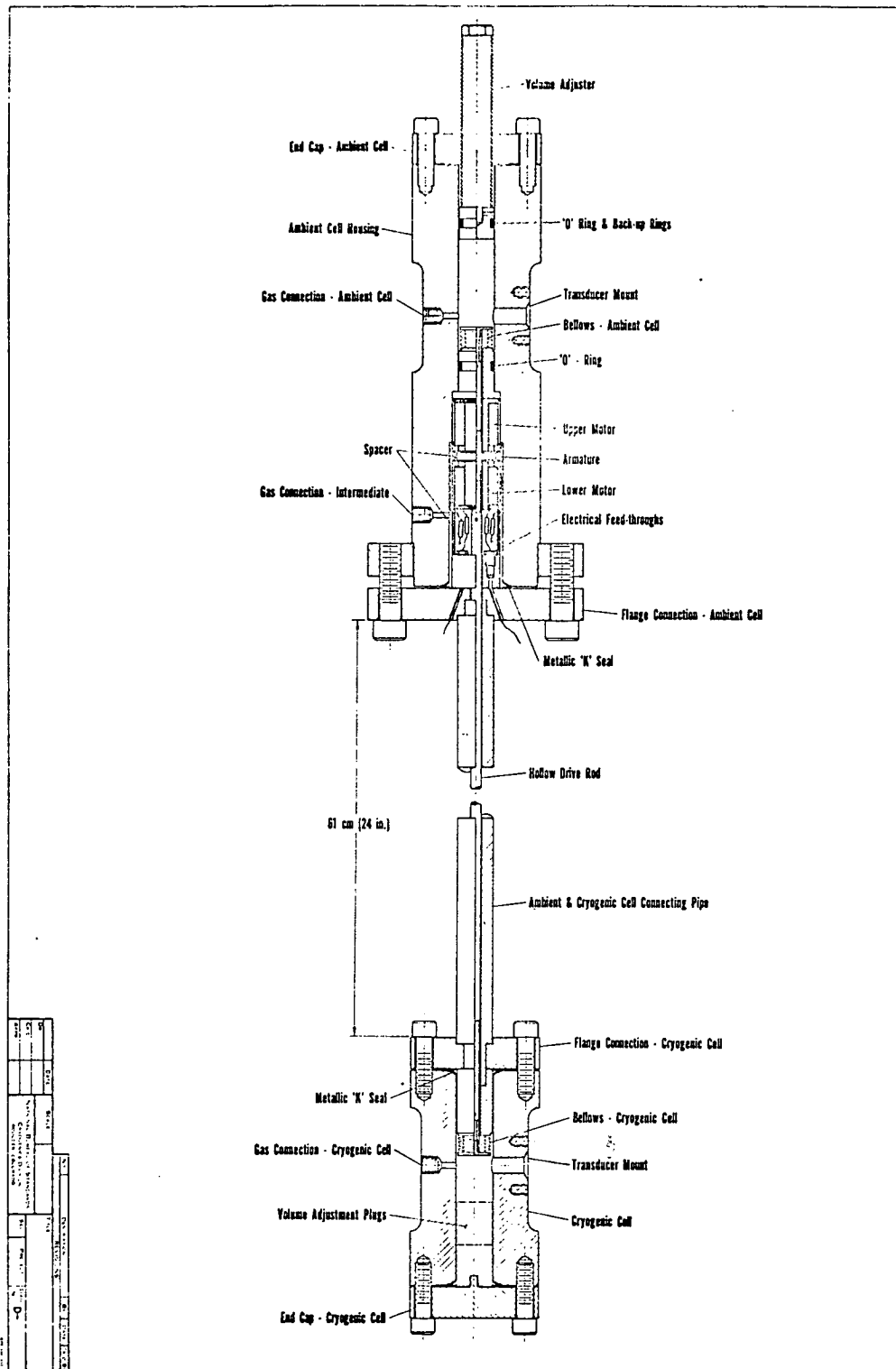


Figure 9.2 Static and dynamic pressure cell assembly.

volume and have in common a single actuating mechanism. The two pressure cells, one at ambient temperature and the other submersed in the cryogen, allow for the simultaneous calibration of a pair of similar pressure transducers (actually, provisions have been made to connect three pressure transducers at each cell making six the total number which can be tested simultaneously).

The static calibration will be made using pressure balances (similar to a dead-weight tester) capable of measuring up to 10,000 psi. As shown in Figure 9.1 two balances will be used; one for low pressure calibration from 0-500 psi and the other for pressures to 10,000 psi. For the 0-10,000 psi balance the sensitivity is better than 0.05 percent of the reading and accuracy is approximately one psi over the entire range. The 0-500 psi pressure balance has comparable sensitivity (0.05 percent of the reading) and an accuracy of 0.1 psi for lower pressures.

The system will monitor pressure transducer performance by the accumulation of output on magnetic tape for complete analysis on the computer. In addition, a small on-line computer will be connected to the system for real-time reduction of data and to provide an immediate indication of transducer performance.

10. REFERENCES AND BIBLIOGRAPHY

REFERENCE DESIGNATION

<u>Category</u>	<u>Symbol</u>	<u>Page</u>
General -----	G	185
Calibration -----	C	190
Pressure Transducers		
Bellows-----	B	192
Bourdon tube-----	Bo	193
Capacitance-----	Ca	194
Diaphragm-----	D	196
Diode-----	Di	197
Electrokinetic-----	E	198
Inductance-----	I	199
Magnetostrictive-----	M	200
Manometer-----	Ma	201
Micromanometers-----	Mi	203
Optical-----	Op	204
Piezoelectric-----	P	205
Potentiometric-----	Po	206
Reluctance-----	Re	207
Strain-----	S	208
Vibrating Wire-----	V	209

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